Evolved Intuitive Ontology: Integrating Neural, Behavioral and Developmental Aspects of Domain-Specificity

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Traditionally, psychologists have assumed that people come equipped only with a set of relatively domain-general faculties, such as “memory” and “reasoning,” which are applied in equal fashion to diverse problems. Recent research has begun to suggest that human expertise about the natural and social environment, including what is often called “semantic knowledge”, is best construed as consisting of different *domains* of competence. Each of these corresponds to recurrent evolutionary problems, is organised along specific principles, is the outcome of a specific developmental pathway and is based on specific neural structures. What we call a “human evolved intuitive ontology” comprises a catalogue of broad domains of information, different sets of principles applied to these different domains as well as different learning rules to acquire more information about those objects. All this is intuitive in the sense that it is not the product of deliberate reflection on what the world is like.

This notion of an intuitive ontology as a motley of different domains informed by different principles was first popularised by developmental psychologists (R. Gelman, 1978; R. Gelman & Baillargeon, 1983) who proposed distinctions between physical-mechanical, biological, social and numerical competencies as based on different learning principles (Hirschfeld & Gelman, 1994). In the following decades, this way of slicing up semantic knowledge received considerable support both in developmental and neuro-psychology. For example, patients with focal brain damage were found to display selective impairment of one of these do-

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mains of knowledge to the exclusion of others (Caramazza, 1998). Neuroimaging and cognitive neuroscience are now adding to the picture of a federation of evolved competencies that has grown out of laboratory work with children and adults.

An illustration: What is specific about faces

The detection and recognition of *faces* by human beings provides an excellent example of a specialised system. Humans are especially good at identifying and recognising large numbers of different faces, automatically and effortlessly, from infancy. This has led many psychologists to argue that the standard human cognitive equipment includes a special system to handle faces.

Convergent evidence for specialization comes from many different sources. In contrast to other objects, the way facial visual information is treated is configural, taking into account the overall arrangement and relations of parts more than the parts themselves (Young, Hellawell, & Hay, 1987; Tanaka & Sengco, 1997). This is strikingly demonstrated by the finding that inverting faces makes them much more difficult to recognize, compared to objects requiring less configural processing (Farah, Wilson, Drain, & Tanaka, 1995). Developmentally, newborn infants quickly orient to faces rather than other stimuli (Morton & Johnson, 1991) and recognise different individuals early (Pascalis, de Schonen, Morton, Deruelle, & et al., 1995; Slater & Quinn, 2001). Neuropsychology has documented many cases of prosopagnosia or selective impairment of face-recognition (Farah, 1994) where the structural processing of objects, object-recognition and even imagination for faces can be preserved while face recognition remains intact (Duchaine, 2000; Michelon & Biederman, 2003). Finally, neuro-imaging studies have reliably shown a specific pattern of activation (in particular, modulation of areas of the fusiform gyrus in the temporal lobe) during identification or passive viewing of faces (Kanwisher, McDermott, & Chun, 1997). Specialised systems may handle the invariant properties of faces (that allow recognition) while other networks handle changing aspects such as gaze, smile and emotional expression (Haxby, Hoffman, & Gobbini, 2002).

Despite this impressive evidence, some psychologists argue that the specificity of face-perception is an illusion, and that human beings simply become expert recognisers of faces by using unspecialised visual capacities. In this view, the newborns' skill in the face-domain may be the result of a special interest in conspecifics that simply makes faces more ecologically important than other objects (Nelson, 2001). Also, one can observe the inversion effect (Diamond & Carey, 1986; Gauthier, Williams, Tarr, & Tanaka, 1998) and fusiform gyrus activation (Gauthier, Tarr, Anderson, Skudlarski, & Gore, 1999; Tarr & Gauthier, 2000) when testing trained experts in such domains as birds, automobiles, dogs or even abstract geometrical shapes (see (Kanwisher, 2000) for a detailed discussion).

In our view, this demonstrates the importance of gradual development, the crucial contribution of relevant experience and that of environmental factors. These are all crucial aspects of functional specialization from evolutionary origins. These points will become clearer as we compare the face-system to other kinds of specialised inferential devices typical of human intuitive ontology.

Features of domain-specific inference systems

The face-recognition system provides us with a good template for the features we encounter in other examples of domain-specific systems.

[1] *Semantic knowledge comprises specialized inference systems.*

It is misleading to think of semantic knowledge in terms of a declarative data-base. Most of the knowledge that drives behavior stems from tacit inferential principles, that is, specific ways of handling information.

In the case of face-recognition, configural processing seems to be a computational solution to the problem of recognizing individuals across time while tracking a surface (the face) that constantly changes in small details, with different lighting or facial expressions.

More generally, we will describe intuitive ontology as a set of computational devices, each characterised by a specific input format, by specific inferential principles and by a specific type of output (which may in turn be input to other systems). Given information that matches the input format of one particular system, activation of that system and production of the principled output are fairly automatic.

[2] *Domains are not given by reality but are cognitively delimited.*

Faces are not a physically distinct set of objects that would be part of "the environment" of any organism. Faces are distinct objects only to an organism equipped with a special system that pays attention to the top front surface of conspecifics as a source of person-specific information.

Moreover, inferential systems are focused not necessarily on objects but on *particular aspects* of objects which is why a single physical object can trigger concurrent activation of several distinct inference systems. For instance, although faces invariably come with a particular expression, distinct systems handle the *Who-is-that?* and *In-What-Mood?* questions (Haxby et al., 2002).

To coin a phrase, the human brain's intuitive ontology is *philosophically incorrect*. That is, the distinct cognitive domains – different classes of objects in our cognitive environment as distinguished by our intuitive ontology – do do not always correspond to real ontological categories – different kinds of "stuff" out there. For instance, the human mind does not draw the line between living and non-living things, or between agents and objects, in the same way as a scientist or a philosopher would do, as we will illustrate below.

[3] *Evolutionary design principles suggest the proper domain of a system.*

The domain of operation of the system is best circumscribed by evolutionary considerations. Natural selection resulted in genetic material that normally results in human brains with a specific capacity for face-recognition. But why should we describe it as being about "faces"? It may seem more accurate to say that it is specialised in "fine-grained, intra-categorical distinctions between grossly similar visual representations of middle-sized objects," as some have argued. But consider this. We observe that the stimuli in question only trigger specific processing if they include a central (mouth-like) opening and two brightly contrasted (eye-like) points above that opening. We should then add these features to our description. The system would then be described as especially good at "fine-grained, intra-categorical […] with a central opening and [etc.]". We could add more and more features to this supposedly "neutral" description of the system.

Such semantic contortions are both redundant and misleading. Inasmuch as the only stimuli corresponding to our convoluted re-description actually encountered during evolution were conspecifics' faces, the re-description is redundant. But it also blurs the functional features of the system, for there are indefinitely many inferences one could extract from presentations of "fine-grained, intra-categorical… etc." (face-like) stimuli, only some of which are relevant to distinctions between persons[1]. A description in terms of functional design provides the best explanation for the system's choice of what is and what is not relevant in faces.

[4] *Evolutionary and actual domains do not fully overlap.*

Without effortful training, the face-recognition system identifies and recognizes what it was designed to expect in its environment. As we saw above, the system may be re-trained, with more effort, to provide identification of objects other than faces, such as birds or cars. In the same way, our evolved walking, running and jumping motor routines can be re-directed to produce ballet dancing. But it is nevertheless the case that they evolved in order to move us closer to resources or shelter and away from predators. The fact that some cognitive system is specialised for a domain *D* does not entail that it invariably or exclusively handles *D, nor does it mean that the specialization cannot be coopted for evolutionarily novel activities.* It means that ancestors of the present organism encountered objects that belong to *D* as a stable feature of the environments where the present cognitive architecture was selected, and that handling information about such objects enhanced fitness.

There may be – indeed, there very often is – a difference between the *proper* (evolutionary) and *actual* domains of a system (Sperber, 1994). On the one hand, the specialised system evolved to represent and react to a set of objects, facts and properties (for instance, flies for the insect-detection system in the frog's visual system). On the other hand, the system actually reacts to a set of objects, facts and properties (e.g. flies *as well as* any small object zooming across the visual field). Proper and actual domains are often different. Mimicry and camouflage use this non-congruence. Non-poisonous butterflies may evolve the same bright colours as poisonous ones to avoid predation by birds. The proper (evolved) domain of the birds' bright-coloured bug avoidance system is the set of poisonous insects, the actual domain is that of all insects that look like them (Sperber, 1994).

[5] *In evolution, you can only learn more if you already know more.*

The face-recognition system does not need to store a description of each face in each possible orientation and lighting condition. It only stores particular parameters for an algorithm that connects each sighting of a face with a person's "face-entry".

Turning to other domains, we find the same use of vast information stores in the environment, together with complex processes required to find and use that information. The lexicon of a natural language (15 to 100 thousand distinct items) is extracted through development from the utterances of other speakers. This constitutes an impressive economy for genetic transmission, as human beings can develop complete fluency without the lexicon being stored in the genome. But this external database is available only to a mind with complex phonological and syntactic predispositions (Pinker & Bloom, 1990; Jackendoff, 2002). In a similar way, the diversity and similarities between animal species are inferred from a huge variety of available natural cues (color, sound, shape, behavior, etc.) but that information is relevant only to a mind with a disposition for natural taxonomies (Atran, 1990).

In general, the more an inference system exploits external sources of information and stable aspects of the cognitive environments, the more computational power is required to home in on that information and derive inferences from it. There is in evolution a general coupling between the evolution of more sophisticated cognitive equipment and the use of more extensive information stored in environments.[although I find this an intuitively compelling assertion, could you back it up a bit more with arguments or evidence about why this is likely to be the case?]

[6] *Each inferential system has a specific learning logic.*

Infants pay attention to faces and quickly recognise familiar faces because they are biased to pay attention to small differences in this domain that they would ignore in other domains.

More generally, knowledge acquisition is informed by domain-specific learning principles (R. Gelman, 1990), that we will review in the following pages. Also, different systems have different developmental schedules, including "windows" of development before or after which learning of a particular kind is difficult. These empirical findings have led developmental psychologists to cast doubt on the notion of a general, all-domain "learning logic" that would govern cognitive development in various domains (Hirschfeld & Gelman, 1994).

[7] *Development follows evolved pathways*

Consider the notion of a ballistic process. This is a process (e.g. kicking a ball) where one has influence over initial conditions (e.g. direction and energy of the kick) but this influence stops there and then, as the motion is influenced only by external factors (e.g. friction). If brain development was one such ballistic system, the genome would assemble a brain with a particular structure and then stop working on it. From the end of organogenesis, the only functionally relevant brain changes would be brought about by interaction with external information. But that is clearly not the case. Genetic influence on many organic structures is pervasive throughout the life span and that is true of the brain too.

We must insist on this, because discussions of evolved mental structures often imply that genetic influence on brain structures is indeed ballistic, so that one can draw a line between function that is specified at birth (supposedly the result of evolution) and function that emerges during development (supposedly the effect of external factors unrelated to evolution). Indeed, this seems to be the starting point of many discussions of "innateness" (Elman, Bates, Johnson, & Karmiloff-Smith, 1996) even though the assumption is biologically implausible[2].

Evolution results not just in a specific set of adult capacities but also in a specific set of developmental pathways that lead to such capacities. This is manifest in the rather circuitous path to adult competence that children follow in many domains. For instance, young children do not build syntactic competence in a simple-to-complex manner, starting with short sentences and gradually adding elements. They start with a one-word stage, then proceed to a two-word stage, then discard that structure to adopt their language's phrase grammar. Such phenomena are present in other domains too, as we will discuss in the rest of this chapter.

[8] *Development requires a normal environment*

Face recognition probably would not develop in a context where people always changed faces or all looked identical. Language acquisition requires people interacting with a child in a fairly normal way. Mechanical-physical intelligence requires a world furnished with some functionally-specialised man-made objects. In this sense inference systems are similar to teeth and stomachs, which need digestible foods rather than intra-venous drips for normal development, or to the visual cortex that needs retinal input for proper development.

What is “normal” about these normal features of the environment is not that they are inevitable or general (food from pills and I.V. drips may become common in the future, dangerous predators have vanished from most human beings’ environments) but that they were generally present in the environment of evolution. Children a hundred thousand years ago were born in an environment that included natural language speakers, man-made tools, gender roles, predators, gravity, chewable food and other stable factors that made certain mental dispositions useful adaptations to those environmental features.

[9] *Inferential systems orchestrate finer-grain neural structures*

The example of face-recognition also shows how our understanding of domain-specificity is crucially informed by what we know about neural structures and their functional specialization. However, the example is perhaps misleading in suggesting a straightforward mapping from functional specialization onto neural specialization.

Cognitive domains correspond to recurrent fitness-related situations or problems (e.g. ‘predators’, ‘competitors’, ‘tools’, ‘foraging techniques’, ‘mate selection’, ‘social exchange’, ‘interactions with kin’, etc.). Should we expect to find neural structures that are specifically activated by information pertaining to one of these domains?

There are empirical and theoretical reasons to expect a rather more complex picture. Neural specificity should not be confused with easily tracked anatomical localisation. Local activation differences, salient though they have become because of the (literally) spectacular progress in neuro-imaging techniques, are not the only index of neural specialization. A variety of crucial differences in brain function consist in time-course differences (observed in ERPs), in neuro-transmitter modulation and in spike-train patterns that are not captured by fMRI studies (Posner & Raichle, 1994; Cabeza & Nyberg, 2000).

In the current state of our knowledge of functional neuro-anatomy, it would seem that most functionally separable neural systems are *more specific* than the fitness-related domains, so that high-level domain-specificity requires the joint or coordinated activation of different neural systems, and indeed in many cases consists largely of the specific coordination of distinct systems. We illustrate this point presently, when we consider the difference between living and non-living things, or the different systems involved in detecting agency.

Living vs. man-made objects: development and impairment

Let us start with the distinction between animal and other living beings on the one hand, and man-made objects on the other. It would seem that the human mind *must* include some assumptions about this difference. Indeed, developmental and cognitive evidence suggests that one can find profound differences between these two domains.

Animal species are intuitively construed in terms of species-specific "causal essences" (Atran, 1998). That is, their typical features and behavior are interpreted as consequences of possession of an undefined, yet causally relevant quality particular to each identified species. A cat is a cat, not by virtue of having this or that external features – even though that is how we recognise it – but because it possesses some intrinsic and undefined quality that one only acquires by being born of cats. This assumption appears early in development (Keil, 1986) so that pre-schoolers consider the "insides" a crucial feature of identity for animals even though they of course only use the "outside" for identification criteria (S. A. Gelman & Wellman, 1991). Also, all animals and plants are categorised as members of a taxonomy. The specific feature here is not just that categories (e.g. 'snake') are embedded in other, more abstract ones ('reptiles') and include more specific ones ('adder'), but also that the categories are mutually exclusive and jointly exhaustive, which is not the case in other domains. Although animal and plant classifications vary between human cultures, the hierarchical ranks (e.g. varietals, genus, family, etc.) are found in all ethno-biological systems and carry rank-specific expectations about body-plan, physiology and behavior (Atran, 1998).

By contrast, man-made objects are principally construed in terms of their *functions*. Although children may sometimes seem indifferent to the absence of some crucial functional features in artefacts (e.g. a central screw in a pair of scissors) (Gentner & Rattermann, 1991), young children are sensitive to such functional affordances (physical features that support function) when they actually *use* tools, either familiar or novel (Kemler Nelson, 1995) and when they try to understand the use of novel objects (Richards, Goldfarb, Richards, & Hassen, 1989). Young children construe functional features in teleological terms, explaining for instance that scissors have sharp blades so they cut (Keil, 1986). Artefacts seem to be construed by adults in terms of their designers' intentions as well as actual use (Bloom, 1996) and pre-schoolers too consider intentions as relevant to an artefact's 'genuine' function (S. A. Gelman & Bloom, 2000), although they are more concerned with the current user's intentions rather than the original creator's.

These differences between domains illustrate what we call inferential principles. The fact that an object is identified as either living or man-made leads to [a] paying attention to different aspects of the object; [b] producing different inferences from similar input; [c] producing categories with different internal structures (observable features index possession of an essence [animals] or presence of a human intention [artefacts]; [d] assembling the categories themselves in different ways (there is no hierarchical, nested taxonomy for artefacts, only juxtaposed kind-concepts).

Neuro-psychological evidence supports this notion of distinct principles. Some types of brain damage result in impaired content or retrieval of linguistic and conceptual information in either one of the two domains. The first cases to appear in the clinical literature showed selective impairment of the living thing domain, in particular knowledge for the names, shapes or associative features of animals (Warrington & McCarthy, 1983; Sartori, Job, Miozzo, Zago, & et al., 1993; Sheridan & Humphreys, 1993; Sartori, Coltheart, Miozzo, & Job, 1994; Moss & Tyler, 2000). But there is also evidence for *double dissociation*, for the symmetrical impairment in the artefact domain with preserved knowledge of living things (Warrington & McCarthy, 1987; Sacchett & Humphreys, 1992). This suggests two levels of organisation of semantic information, one comprising modality-specific or modality-associated stores and the other comprising distinct category-specific stores (Caramazza & Shelton, 1998).

Living vs. man-made objects: evolved and neural domains

There may be an over-simplification in any account of semantic knowledge that remains at the level of such broad ontological categories as "living" and "man-made". For instance, it is not clear that children really develop domain-specific understandings at the level of the "living thing" and "man-made" categories. All the evidence we have concerns their inferences on medium-size animals (gradually and only partly extended to bugs, plants) and on manipulable tools with a direct, observable effect on objects (not houses or dams or lampposts).

Evolutionary consideration would suggest that specificity of semantic knowledge will be found at a more specific level, corresponding to situations that carry [specific] particular fitness consequences. In evolutionary terms, one should consider not just the categories of objects that are around an organism but also the kinds of interaction likely to impinge on the organism's fitness. From that standpoint, humans certainly do not interact with "living things" in general. Living things comprise plants, bacteria, and middle-sized animals including human beings. Human beings interact very differently with predators, prey, potential foodstuffs, competitors, parasites. Nor do humans handle "artefacts" in general. Man-made objects include foodstuffs, tools and weapons, buildings, shelters, visual representations, as well as paths, dams and other modifications of the natural environment. Tools, shelters and decorative artefacts are associated with distinct activities and circumstances. So we should expect the input format and activation cues of domain-specific inference systems to reflect this fine-grained specificity.

Indeed, this hypothesis of a set of finer-grained systems receives some support from behavioral and developmental studies and most importantly from the available neuro-functional evidence. A host of neuroimaging studies, using both PET and fMRI scans, with either word- or image-recognition or generation, has showed that living things and artefacts trigger significantly different cortical activations (Martin et al., 1994; Perani et al., 1995; Spitzer, Kwong, Kennedy, & Rosen, 1995; Martin, Wiggs, Ungerleider, & Haxby, 1996; Spitzer et al., 1998; Moore & Price, 1999; Gerlach, Law, Gade, & Paulson, 2000). However, the results are not really straightforward or even consistent[3]. Despite many difficulties, what can be observed is that [a] activation in some areas (pre-motor in particular) is modulated by artefacts more clearly than by other stimuli, [b] there is a more diffuse involvement of temporal areas for both categories, [c] one finds distinct activation maps rather than privileged regions.

The naming of artefacts, or even simple viewing of pictures of artefacts, seems to result in pre-motor activation. Viewing an artefact-like object automatically triggers the search for (and simulation of) motor plans that involve the object in question. Indeed, the areas activated (premotor cortex, anterior cingulate, orbito-frontal) are all consistent with this interpretation of a motor plan that is both activated *and* inhibited. This suggests that "man-made object" is probably not the right criterion here. Houses are man-made but do not afford motor plans that include handling. If *motor* plans are triggered, they are about *tools* rather than man-made objects in general (Moore & Price, 1999). A direct confirmation can be found in a study of *manipulable* versus *non-manipulable* artefacts, which finds the classical left ventral frontal (pre-motor) activation only for the former kind of stimuli (Mecklinger, Gruenewald, Besson, Magnie, & Von Cramon, 2002).

Neuro-imaging evidence for the animal domain is less straightforward. Some PET studies found specific activation of the lingual gyrus for animals, but this is also sometimes activated by artefact naming tasks (Perani et al., 1995). Some infero-temporal areas (BA20) are found to be exclusively activated by animal pictures (Perani et al., 1995), as are some occipital areas (left medial occipital) (Martin et al., 1996). The latter activation would only suggest higher modulation of early visual processing for animals. This is consistent with the notion, widespread in discussions of domain-specific selective impairment, that identification of different animal species requires finer-grained distinctions than that of artefacts: animals of different species (cat, dog) often share a basic *Bauplan* (trunk, legs, head, fur) and differ in details (shape of head, limbs, etc.), while tools (e.g. screwdriver, hammer) differ in overall structure. Animal-specific activations of the posterior temporal lobe seem to vanish when the stimuli are easier to identify (Moore & Price, 1999) which would confirm this interpretation as an effect of fine-grained, relatively effortful processing[4].

Neuro-imaging findings and developmental evidence converge in supporting the evolutionarily plausible view, that inference systems are not about ontological categories like “man-made object” or “living thing” but about types of situations, such as “fast identification of potential predator-prey” or “detection of possible use of tool or weapon”.

Advantages of mind-reading

A central assumption of human intuitive ontology is that some objects in the world are driven by internal states, in particular by goals and other representational states such as desires and beliefs. This has received great attention in developmental models of “theory of mind”. The term designates the various tacit assumptions that govern our intuitive interpretation of other agents’ (and our own) behavior as the outcome of invisible states like beliefs and intentions.

On the basis of tasks such as the familiar “false-belief” tasks, developmental psychologists suggested that the understanding of belief as representational and therefore possibly false did not emerge in normal children before the age of four (Perner, Leekam, & Wimmer, 1987), and did not develop in a normal way in autistic individuals (Baron-Cohen, Leslie, & Frith, 1985). More recently, other paradigms that avoided some difficulties of classical tasks have demonstrated a much earlier-developed appreciation of false belief or mistaken perception (Leslie & Polizzi, 1998).

Having a rich explanatory psychological model of other agents’ behavior is a clear example of a cognitive adaptation (Povinelli & Preuss, 1995). Indeed, above a certain degree of complexity, it is difficult to predict the behavior of a complex organisms without taking the “intentional stance”, that is, describing it in terms of unobservable entities like intentions and beliefs (Dennett, 1987). The difference in predictive power is enormous even in the simplest of situations. A judgement like “So-and-so tends to share resources” may be based on observable regularities (So-and-so sometimes leaves aside a share of her food for me to pick up). By contrast, a judgement like “So-and-so is generous” can provide a much more reliable prediction of future behavior, by interpreting past conduct in the light of intentions and beliefs and also knowing in what cases evidence counts or not towards a particular generalisation (e.g. “So-and-so did not leave me have a share of her food yesterday but that’s because she had not seen I was there”, “She is generous only with her kin”, “She is generous with friends”, etc.)

As in other cases where apparently broad domains are actually more fine-grained, we might ask whether the convenient term “theory of mind” actually refers to a single inference system or rather a collection of more specialised systems, whose combination produces typically human “mind-reading”. The salience of one particular experimental paradigm (false-belief tasks) together with the existence of a specific pathology of mind-reading (autism) might suggest that “theory of mind” is a unitary capacity, in many ways akin to a scientific account of mind and behavior (Gopnik & Wellmann, 1994). This also led to speculation as to which species did or did not have “theory of mind” and at what point in evolution it appeared in humans (Povinelli & Preuss, 1995).

There are two distinct origin scenarios for our capacity to understand intentional agency, to create representations of other agents’ behavior, beliefs and intentions. A widely accepted "social intelligence" scenario is that higher primates evolved more and more complex intentional psychology systems to deal with social interaction. Having larger groups, more stable interaction, and more efficient co-ordination with other agents all bring out, given the right circumstances, significant adaptive benefits for the individual. But they all require finer and finer grained descriptions of other agents' behaviors. Social intelligence triggers an arms-race resulting from higher capacity to manipulate others and a higher capacity to resists such manipulation (Whiten, 1991). It also allows the development of coalitional alliance, based on a computation of other agents' commitments to a particular purpose (hunting, warfare) (Kurzban & Leary, 2001), as well as the development of friendship as an insurance policy against variance in resources (Tooby & Cosmides, 1996).

Another possible account is that (at least some aspects of) theory of mind evolved in the context of predator-prey interaction (Barrett, 1999), this volume). A heightened capacity to remain undetected by either predator or prey, as well as a better sense of how these other animals detect us, are of obvious adaptive significance for survival problems such as eating and avoiding being eaten. Indeed, some primatologists have speculated that detection of predators may have been the primary context for the evolution of agency concepts (Van Schaik & Van Hooff, 1983). In the archaeological record, changes towards more flexible hunting patterns in modern Humans suggest a richer, more intentional representation of the hunted animal (Mithen, 1996). Hunting and predator-avoidance become much better when they are more flexible, that is, informed by contingent details about the situation at hand, so that one does not react to all predators or prey in the same way.

These interpretations are complementary, if we remember that "theory of mind" is probably not a unitary capacity to produce mentalistic accounts of behavior, but a suite of distinct capacities. Humans throughout evolution did not interact with generic *intentional agents*. They interacted with predators and prey, with other animals and with conspecifics. The latter consisted of helpful parents and siblings, potentially helpful friends, helpless offspring, dangerous rivals, attractive mates. Also, successful interaction in such situations requires predictive models for general aspects of human behavior (a model of motivation and action, as it were) as well as particular features of each individual (a model of personality differences).

A suite of agency-focused inference engines

These different, situation-specific models themselves orchestrate a variety of lower-level neural capacities, all of which focus on particular features of animate agents and take some form of "intentional stance", that is, describe these features in terms of stipulated beliefs and intentions.

One of the crucial systems is geared at detecting *animate motion*. For some time now, cognitive psychologists have been able to describe the particular physical parameters that makes motion seem animate. This system takes as its input format [a] particular patterns of motion(Michotte, 1963; Schlottman & Anderson, 1993; Tremoulet & Feldman, 2000) and delivers as output an automatic interpretation of motion as animate. The system seems to develop early in infants (Rochat, Morgan, & Carpenter, 1997; Baldwin, Baird, Saylor, & Clark, 2001). These inferences are sensitive to category-specific information, such as the to the kind of object that is moving and the context (R. Gelman, Durgin, & Kaufman, 1995; Williams, 2000).

Animates are also detected in another way, by tracking *distant reactivity*. If a rock rolls down a hill, the only objects that will react contingently to this event at a distance – without direct contact - are the animates that turn their gaze or their head to the object, jump in surprise, run away, etc.). There is evidence that infants can detect causation at a distance (Schlottmann & Surian, 1999). This would provide them with a way of detecting as "agents" those objects that *react* to other objects' motion. In experimental settings, infants who have seen a shapeless blob reacting to their own behavior then follow that blob's orienting as if the (eyeless, faceless) blob was gazing in a particular direction (Johnson, Slaughter, & Carey, 1998). There is also evidence that detection of reactivity modulates particular neural activity, distinct from that involved in the interpretation of intentions and beliefs (Blakemore, Boyer, Pachot-Clouard, Meltzoff, & Decety, 2003).

A related capacity is *goal-ascription*. Animates act in ways that are related to particular objects and states in a principled way (Blythe, Todd, & Miller, 1999). For instance, their trajectories make sense in terms of *reaching* a particular object of interest and *avoiding* non-relevant obstacles. Infants seem to interpret the behavior of simple objects in that way. Having seen an object take a detour in its trajectory towards a goal to avoid an obstacle, they are surprised if the object maintains the same trajectory once the obstacle is removed (Csibra, Gergely, Biro, Koos, & Brockbank, 1999), an anticipation that is also present in chimpanzees (Uller & Nichols, 2000)[5].

A very different kind of process may be required for *intention-ascription*. This is the process whereby we interpret some agent's behavior as efforts towards a particular state of affairs, e.g. seeing the banging of the hammer as a way of forcing the nail though the plank. There is evidence that this capacity develops early in children. For instance, young children imitate successful rather than unsuccessful gestures in the handling of tools (Want & Harris, 2001) and can use actors' apparent emotions as a clue to whether the action was successful or not (Phillips, Wellman, & Spelke, 2002). Young children can choose which parts of an action to imitate even if they did not observe the end result of the action (Meltzoff, 1995)[6]. The capacity is particular important for humans, given a history of tool-making that required sophisticated perspective-taking abilities (Tomasello, Kruger, & Ratner, 1993).

The capacity to engage in *joint attention* is another crucial foundation for social intelligence (Baron-Cohen, 1991). Again, we find that human capacities in this respect are distinct from those of other primates, and that they have a specific developmental schedule. The most salient development occurs between 9 and 12 months and follows a specific order: first, joint engagement (playing with an object and expecting a person to cooperate); second, communicative gestures (such as pointing); third, attention following (i.e. following people's gaze) and more complex skills like gaze alternation (going back and forth between the object and the person) (Carpenter, Nagell, & Tomasello, 1998). In normal adults, following gaze and attending to other agents' focus of attention are automatic and quasi-reflexive processes (Friesen & Kingstone, 1998). The comparative evidence shows that chimpanzees take gaze as a simple clue to where objects of interest may be, as opposed to taking it as indicative of the gazer's state and intentions, as all toddlers do (Povinelli & Eddy, 1996a, 1996b).

A capacity for relating *facial cues to emotional states* is also early developed and seems to achieve similar adult competence in human cultures (Ekman, 1999; Keltner et al., 2003). Five-month old infants react differently to displays of different emotions on a familiar face (D'Entremont & Muir, 1997). It seems that specific neural circuitry is involved in the detection and recognition of specific emotion types (Kesler/West et al., 2001), distinct from the general processing of facial identity. These networks partly overlap with those activated by the emotions themselves. For instance, the amygdala is activated both by the processing of frightening stimuli and frightened faces (Morris et al., 1998). The detection of emotional cues presents autistic patients with a difficult challenge (Adolphs, Sears, & Piven, 2001; Nijokiktjien et al., 2001), compounded by their difficulty in understanding the possible reasons for other people's different emotions. Williams syndrome children seem to display a dissociation between preserved processing of emotion cues and impaired understanding of goals and beliefs ("theory of mind" in the narrow sense), which would suggest that these are supported by distinct structures (Tager-Flusberg & Sullivan, 2000).

This survey is certainly not exhaustive but should indicate the variety of systems engaged in the smooth operation of higher "theory of mind" proper, that is, the process of interpreting other agents' (or one's own) behavior in terms of beliefs, intentions, memories and inferences. Rudimentary forms of such mind-reading capacities appear very early in development (Meltzoff, 1999) and develop in fairly similar forms in normal children. Although familial circumstances can boost the development of early mind-reading (Perner, Ruffman, & Leekam, 1994), this is only a subtle influence on a developmental schedule that is quite similar in many different cultures (Avis & Harris, 1991).

These various systems are activated by very different cues, they handle different input formats and produce different types of inferences. They are also, as far as we can judge given the scarce evidence, based on distinct neural systems. Early studies identified particular areas of the medial frontal lobes as specifically engaged in "theory-of-mind" tasks (Happe et al., 1996). There is also neuro-psychological evidence that right-hemisphere damage to these regions results in selective impairment of this capacity (Happe, Brownell, & Winner, 1999). Note, however, that in both cases we are considering false-belief tasks, that is, the *explicit* description of another agent's *mistaken* beliefs. Actual mind-reading requires other associated components, many of which are associated with distinct neural systems. The detection of gaze and attentional focus jointly engages STS and parietal areas (Allison, Puce, & McCarthy, 2000; Haxby et al., 2002). The detection of various other types of socially relevant information also activates distinct parts of STS (Allison et al., 2000). The identification of agents as reactive objects depends on selective engagement of superior parietal areas (Blakemore et al., 2003). The simple discrimination between animate and inanimate motion is probably related to joint specific activation of some MT/MST structures as well as STS (Grossman & Blake, 2001).

Different kinds of encounters with intentional agents provide contexts in which *different* cognitive adaptations result in increased fitness. Predator-avoidance places a particular premium on biological motion detection and the detection of reactive objects. Social interaction requires the early development of a capacity to read emotions on faces, but also the later development of a sophisticated simulation of other agents' thoughts. Dependence on hunting favours enhanced capacities for deception. The collection of neural systems that collectively support mind-reading is the result of several distinct evolutionary paths.

Solid objects and bodies

We argued that domain-specific inference systems are not so much focused on a specific kind of object (ontological category) as on a certain aspect of objects (cognitive domain). A good example of this is the set of inferential principles that help make sense of the physical properties and behavior of solid objects – what is generally called an "intuitive physics" in the psychological literature (Kaiser, Jonides, & Alexander, 1986).

The main source of information for the contents and organisation of "intuitive physics" comes from infant studies (Spelke, 1988; Baillargeon, Kotovsky, & Needham, 1995; Spelke, 2000) that challenged the Piagetian assumption, that the development of physical intuitions followed motor development (Piaget, 1930). The studies have documented the early appearance of systematic expectations about objects as units of attention (Scholl, 2001) [7], in terms of solidity (objects collide, they do not go through one another) continuity (an object has continuous, not punctuate existence in space and time) or support (unsupported objects fall) (Spelke, 1990; Baillargeon et al., 1995). Also, a distinction between the roles of agent and patient in causal events seems accessible to infants (Leslie, 1984). Action at a distance is not intuitively admitted as relevant to physical events (Spelke, 1994).

However, the picture in terms of evolved systems may be slightly more complicated than that. The fact that many species manipulate the physical world in relatively agile and efficient ways does not necessarily entail that they do that on the basis of *similar* intuitive physics. In a series of ingenious experiments, Povinelli and colleagues have demonstrated systematic differences between chimpanzees and human infants, (Povinelli, 2000). The chimpanzees' physical assumptions are grounded in perceptual generalisations, while those of infants seem based on assumption of underlying, invisible qualities, such as force or centre of mass (Povinelli, 2000). Also, human beings interact with different kinds of physical objects. In our cognitive environment, we find inert objects (like rocks), objects that we make (food, tools) and living bodies (of conspecifics or other animals). Interaction with these is likely to pose different problems and result in different kinds of principles.

The development of coherent action-plans and motor behavior is crucial in terms of brain development – the infant brain undergoes massive change in that respect, and the energy expended in motor training is enormous in the first year of life – and in evolutionary terms too. The effects of such development and the underlying systems are somewhat neglected in models of "intuitive physics". This is all the more important, as neural and behavioral evidence suggests that the development of action-oriented systems and their neural implementation may be distinct from that of intuitive physics in general. That is to say, it may well be the case that young children and adults develop, not one general intuitive physics that spans the entire ontological category of medium-sized solid objects, but two quite distinct systems: one focused on these solid objects, their statics and dynamics, and the other one focused on biological motion. An interesting possible consequence is neural systems' representations of physical processes are somewhat redundant, as the same physical event is represented in two distinct ways, depending on the kind of object involved.

So far, there is little direct evidence for dedicated neural systems handling representations of the physical behavior of solid objects. Many systems are involved, most of which are not exclusively activated by intuitive physical principles. There are few neuro-imaging studies of physical or mechanical violations of the type used in developmental paradigms, but the few we have find involvement of such general structures as MT/V5 (generally involved in motion processing) and parietal attentional systems (Blakemore et al., 2001).

That biological motion is a special cognitive domain is not really controversial. In the same way as configural information is specially attended to in faces and ignored in other displays, specific processes track biological motion, that is, natural movements of animate beings (people and animals) such as walking, grasping, etc. (Johansson, 1973; Ahlstrom, Blake, & Ahlstrom, 1997; Bellefeuille & Faubert, 1998). There is now some evidence that dedicated neural structures track biological motion (see review in (Decety & Grezes, 1999)), with specific activation in STS, as well as medial cerebellum, on top of the regular activation of MT-MST for coherent motion (Grezes, Costes, & Decety, 1998; Grossman & Blake, 2001). These systems trigger specific inferences about the behavior of biological objects (Heptulla-Chatterjee, Freyd, & Shiffrar, 1996).

The evidence also suggests that inferences about living bodies are grounded in motor-planning systems. Recent neuro-imaging evidence has given extensive support to the notion that perception of other agents' motion, own motor imagery and motor planning, as well as interpretation of goals from this motor imagery, are all tightly integrated (Blakemore & Decety, 2001). That is, perception of biological motion triggers the formation of equivalent motor plans that are subsequently blocked, probably by inhibitory influences from such structures as the orbito-frontal cortex. Now motor plans include specific expectations about the behavior of bodies and body-parts. In this sense they may be said to include a separate domain of intuitive physics.

Natural numbers and natural operations

Numerical cognition too illustrates how cognitive domains can diverge from ontological categories. Numerical processes could in principle consist in a single "numerosity perception" device. In fact, different processes are in charge of different aspects of number in different situations.

Numerical competence is engaged in a whole variety of distinct behaviors. Children from an early age can estimate the magnitude or continuous "numerousness" of aggregates (e.g. they prefer more sugar to less); they also estimate relative quantities of countable objects (a pile of beads is seen as "bigger" than another); they count objects (applying a verbal counting routine, with number tags and recursive rules, to evaluate the numerosity of a set); they produce numerical inferences (e.g. adding two numbers); they retrieve stored numerical facts (e.g. the fact that two times six is twelve).

This variety of behaviors is reflected in a diversity of underlying processes. Against the parsimonious but misleading vision of a unitary, integrated numerical capacity, many findings in behavioral, developmental, neuro-psychological and neuro-imaging studies converge to suggest a variety of representations of numbers and a variety of processes engaged in numerical inference (Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999). In particular, one must distinguish between a pre-verbal, analogue representation of numerosities on the one hand and the verbal system of number-tags and counting rules on the other (Gallistel & Gelman, 1992)[8].

This division is confirmed by neuro-psychological and neuro-imaging studies (Dehaene et al., 1999). One system is principally modulated by exact computation, recall of mathematical facts and explicit application of rules, engaging activation of (mostly left hemisphere) inferior prefrontal cortex as well as areas typically activated in verbal tasks. The engagement of parietal networks in number estimation suggests a spatial representation of magnitudes, supported by the fact that magnitude estimation is impaired in subjects with spatial neglect, and can be disrupted by transcranial magnetic stimulation of the angular gyrus[9]. The analogue magnitude system encodes different numerosities as different points (or, less strictly, fuzzy locations) along a “number line”, an analogical and incremental representation of magnitudes. The other network is engaged in approximation tasks and comparisons, activating bilateral inferior parietal cortex.

The distinction between systems is also relevant to development of the domain. To produce numerical inferences, children need to integrate the representations delivered by the two different systems. The first one is the representation of numerosity provided by magnitude estimation. The second one is the representation of object identity. Individuated objects allow inferences such as (1-1=0) or (2-1≠2) which are observed in infants in dishabituation studies (Wynn, 1992, 2002). The acquisition process requires a systematic mapping or correspondence between two distinct representations of the objects of a collection (R. Gelman & Meck, 1992).

What can we say about the evolutionary history of these distinct capacities? Let us begin with magnitude estimation, the capacity to judge relative amounts or compare a set to some internal benchmark, without verbal counting. Two kinds of facts are relevant here. One is the experimental comparative evidence, showing that magnitude estimation exists in a variety of animals. Indeed, animals studies led to the best analytical model for this capacity, the notion of a counter or *accumulator* (Meck, 1997). The assumption in such models is that animals possess an event counter that can [a] trigger a specific physiological event with each occurrence of an event (not necessarily linked to event-duration) and [b] store the accumulated outcome of events in some accessible register for comparisons. Such a counter would provide an analogue representation whose variance would increase with the magnitudes represented, in keeping with the available human and animal evidence (Gallistel & Gelman, 1992). There has probably been a long history of selection for magnitude estimation and comparison in humans, as this capacity is required in the sophisticated foraging practiced by human hunter-gatherers (Mithen, 1990).

Verbal counting is an entirely different affair. In the course of human history, most societies made do with rudimentary series like “singleton – pair – triplet – a few – many” (Crump, 1990). More elaborated, recursive combinatorial systems that assign possible verbal descriptions to any numerosity are rarer in origin, though much more frequent among modern human societies. A number system is a highly “contagious” kind of cultural system, generally triggered by sustained trade. Finally, most literate societies also developed numerical notation systems, the most efficient of which are place systems where the positions of different symbols stand for the powers of a base.

These recent historical creations require cultural transmission, in the form of exposure to specific behaviors (counting, noting numbers). However, “exposure” is not a causal explanation. Cultural material is transmitted inasmuch as it “fits” the input formats of one or several evolved inference systems. It may be relevant to see number systems, like literacy, as cultural creations that “hijack” prior cognitive dispositions by mimicking the input format of inference systems. This would be another case where the actual and evolved domains of a system only partly overlap. Systematic verbal counting requires a sophisticated sense of *numerical individuation*, that is, an intuition that an object may be perfectly similar to another and yet be a different instance. This seems to develop early in human infants (Xu & Carey, 1996).

The evolved brain is not philosophically correct

The set of systems that we described above constitutes an intuitive ontology. We must keep in mind that this system is formally distinct from a catalogue of *actual* ontological categories, and also from *scientific* ontologies. That a cognitive ontology may depart from actual ontological categories is a familiar point in semantics (Jackendoff, 1983). As we have showed here, there are many discrepancies between the world as science or commonsense see it, and the kinds of objects in the world between which brain systems distinguish. The cumulative findings of neuropsychology, neuro-imaging and adult behavioral studies converge in suggesting a complex neural architecture, with many specialized systems. These systems do not correspond to the classical 'domains' of domain-specificity (e.g., "intuitive psychology," "intuitive physics"). Not only are they finer-grained than broad ontological categories; they also frequently cross ontological boundaries, by focusing on aspects of objects that can be found in diverse ontological categories. In other words, the evolved brain is not philosophically correct.

Although we characterized this particular combination of inference systems as specifically human, we do not mean to suggest that its emergence should be seen as the consequence of a unique hominization process. That is, the various systems probably have very different evolutionary histories. While some of them may well be very recent – consider for instance the high-level description of other agents' behaviors in terms of beliefs and intentions – some are certainly older. We alluded to this point in our description of intuitive physics, most likely an aggregate of different systems, some of which are far older than others.

We think that research in the organisation of human semantic knowledge should benefit from the combination of evolutionary, neural and developmental evidence of the kind summarised here. Research in the field has too often proceeded in the following way: [1] identify an ontological distinction (for instance that between living things and man-made artefacts); [2] develop specific hypotheses and gather empirical evidence for domain-specific principles and developmental patterns that differ between ontological categories; [3] try to integrate neural structures into this picture – often with much more difficulty than was expected.

We propose a slightly different agenda for the next stage of research in the field. We propose that step [1] should be informed by precise evolutionary considerations. This leads to a re-phrasing of many classical distinctions (including that between living things are artefacts) in terms of species-specific ancestral situations, as we argued throughout this chapter. We should also rethink step [2]. Too often, cognitive development is viewed as a ballistic system. In that view, genes provide a newborn infant's mental dispositions and environments provide all the subsequent changes. This, as we argued, is biologically implausible. We may anticipate great progress in our understanding of how genes drive not just the starting point but also the developmental paths themselves. This suggests a range of hypotheses about the way mental systems are primed to use specific information to create mature competencies. This change in the way we see development should lead more naturally to step [3], to the formulation of conceptual specificity in terms of neural systems.

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[1] For instance, faces vary in complexion with the varying colour temperature of daylight during the day; complexion and features change with increased blood-pressure when one's head is lower than the rest of the body; overall face-size is correlated with gender; complexion in women is altered by child-bearing; and many others. There is no evidence that human minds register this kind of information.

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[2] Perhaps because they are mammals, many philosophers and cognitive scientists are somehow fixated on birth as the crucial cutting-off that separates evolutionary factors from environmental ones. As we said, genes influence development after birth. Conversely, note that fetuses receive a lot of external information before birth (which is why for instance they are prepared for the intonation contour of their mother's language).

[3] Many early PET studies (and to some extent more recent fMRI ones) reported specific regions activated by artefacts or animals. However, many of these findings were not replicated. Also, in many of these studies the variety of activation peaks reported for either type of stimuli cannot plausibly be described as constituting a functional network. That is, there is no clear indication that joint involvement of such areas is required for the processing of such stimuli. The gross anatomy does not suggest particular and exclusive connectivity between those regions either. Finally, some of the findings may turn out to be false positives (Devlin, Russell, Davis, Price, & Moss, 2002).

[4] High inter-personal variability of activations, especially for the animal domain, is often seen as a major difficulty in such studies (Spitzer et al., 1998). It makes reports of average activations in a group of subjects especially vulnerable to statistical artefacts (Devlin et al., 2002). However, the fact that maps vary from one subject to another does not entail that there is no stable domain-based, subject-specific differentiation of activation (Spitzer et al., 1998).

[5] Goal-ascription, in this sense, may not require the attribution of *mental* or *representational* states to the goal-driven animate. All the system does, in view of the extant evidence, is [a] consider an object, [b] consider an other object (the goal) as relevant to the first one's motion, [c] anticipate certain trajectories in view of that goal. All this could be done by, e.g. considering physical goals as endowed with some "attractive force" rather than considering the animate as striving to reach it.

[6] There is also evidence that even infants "parse" the flow of action into discrete segments that correspond to different goals (Baldwin et al., 2001). In adults, this segmentation is probably accomplished by distinct neural networks (Zacks et al., 2001).

[7] This is not self-evident, especially as many classical models of attention describe surfaces, segments of the visual world and more generally *features* rather than whole objects as the basic unit of information for attentional systems (Heslenfeld, Kenemans, Kok, & Molenaar, 1997).

[8] Along with these two important systems, additional representational stores may be dedicated to particular numerical facts in semantic memory, to numbers represented in distinct notations, and to higher-level mathematical knowledge (Campbell, 1994; Lee & Karmiloff-Smith, 1996).

[9] Magnitude estimation tasks are impaired in patients with spatial neglect (Zorzi, Priftis, & Umilta, 2002). Also, TMS results support this link between parietal spatial networks and numbers, since stimulation of the angular gyrus seems to disrupt approximate magnitude estimations (Gobel, Walsh, & Rushworth, 2001).