A Correlation-Based Mechanism of Representational Development

David H. Rakison
Carnegie Mellon University

In this article, I present a theory of infant concept development that stresses continual representational enrichment. Fundamental to this process is that infant possess a sensitive perceptual system, which is biased to detect and attend to particular aspects of the visual array, and a domain general associative learning mechanism, which encodes correlations among static and dynamic attributes. It is argued that infants’ categories appear to change qualitatively in the second year of life, though the underlying process of conceptual change is that of gradual, incremental learning. To support this view, I present evidence from empirical studies on infants’ ability to attend to static and dynamic correlations as well as recent connectionist simulations of early categorization. The empirical evidence provides a direct demonstration that infants develop the ability to detect and learn the associations that exist among specific features – in this case, object parts and the functional or motion-related properties to which they are causally related – and the connectionist models suggest, among other things, that a form of continuous Hebbian-based learning can lead to qualitative changes in representational content and structure.

One of the most fundamental, yet seemingly intractable issues within cognitive science is to explain how objects in the world “seem to hang together” in coherent categories (Murphy & Medin, 1985). Why is it, for example, that cats, dogs, zebras, and elephants are considered to fall into the same category, or that birds, mosquitoes, planes, and UFOs likewise can be grouped together in some meaningful way? At stake in finding a resolution to this issue is not only the nature of conceptual structure but also its content; that is, the form in which concepts are represented, and the information about things in the world that is included within these concepts.1

Theories to explain how categories cohere tend to fall into one of two groups. On the one hand, it has been argued that objects are categorized as belonging to a particular category on the basis of similarity. This view lays emphasis on the idea that entities, objects, and events in the world are naturally clustered into similar kinds, and our conceptual system takes advantage of these invariant resemblance relations. Among these approaches are included the classical view – in which concepts are represented by certain category defining attributes (see Smith & Medin, 1981, for a review) – the probabilistic view – in which concepts are represented in terms of characteristic rather than defining features (e.g., Rosch, 1978; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976) – and the exemplar view whereby concepts are represented by individual category members (Medin & Schaffer, 1978).2 On the other hand, it has been proposed that theories – by which is meant a mental “explanation” of causal relations – not only forms the cornerstone for knowledge of things in the world but also organizes the structure of that knowledge. According to this view, attribute matching and similarity are inherently insufficient to explain category coherence because they are too unconstrained; that is, they do not explain which attributes should be

---

1 Throughout this manuscript, I use the term category to refer to groupings or classes of objects in the world and the term concept to refer to the mental representations of these objects.

2 I will use the term property to refer to any predicate that can be asserted of some or all of the members of a category (Hampton and Dubois, 1993). The terms attribute and feature, refer to particular aspects of a property: An attribute or feature is a property with a number of mutually exclusive states or possibilities. Thus the property “is round” can be considered in terms of the attribute “shape”.

---
important in category membership decisions. This theory, as it is often called, emphasizes that concepts are rooted in knowledge that embodies a theory of the world, and the features that are diagnostic for category membership are those that are less perceptible, or even nonobservable (Medin & Ortony, 1989; Murphy & Medin, 1985). For instance, theoretical knowledge about the nature of air speed and uplift connects “has flies” to “wings” as part of the concept of airplane, and a lay theory of genetic structure and the reproductive system allow us to determine to which species a particular animal exemplar belongs.

These two general views of concepts and category coherence are, to some extent, also in conflict within the literature on category and concept development within the first years of life. It is well established that, whether one is talking about geometric forms (Riccuiti, 1965), faces (Cohen & Strauss, 1979), or a host of real-world objects such as cats, dogs, mammals, or furniture (Behl-Chadha, 1996; Eimas & Quinn, 1994), infants’ earliest categories are grounded in perceptual information. These perceptual categories, which are formed on the basis of the surface appearance of things, are most likely represented in terms of a perceptual prototype or schema (Mandler, 1997; Quinn & Eimas, 1997). According to some theorists (e.g., Eimas, 1994; Jones & Smith, 1993), this perceptual information continues to play a primary role in category and concept formation throughout the lifespan. In contrast to this view, it has been argued that within the first year of life infants start to develop concepts that allow them to form categories that cohere not because of how things look but rather because of a shared meaning (Mandler, 1992, 2000). For example, rather than infants grouping together various mammals because they all possess four legs or have a similar shape, it is posited that the basis for early category coherence is knowledge concerning the fact that mammals are self-propelled entities that can act as agents. Such conceptual or nonobvious knowledge – that which “cannot be seen” (Keil, 1989) - putatively allows the young categorizer to overlook perceptual similarity and instead group objects on the basis of a shared taxonomy. This acquisition of knowledge about the deeper, nonobvious properties of objects is thought to start in infancy with motion- and psychological-related characteristics (e.g., Gelman, 1990; Mandler, 1992; Woodward, 1998; for a review see Rakison & Poulin-Dubois, in press), but it is not until between 2 and 4 years of age that children are believed to incorporate information about biological characteristics into their concepts of objects (e.g., Gelman & Coley, 1990; Gelman & Markman, 1986, 1987).

In addition to the problem of category coherence, developmentalists also face the issue of how nonobvious information becomes incorporated into infants’ representations; that is, what are the processes of conceptual change. It has long been assumed that this developmental trend is best characterized as a “perceptual to conceptual shift” with early categories formed on the basis of perceptual similarity and later categories, often following a stage-like change in representational structure and content, formed predominantly on the basis of conceptual properties (e.g., Gelman & Markman, 1986, 1987; Keil, 1981, 1991; Mandler, 1988, 1992, 2000; Murphy & Medin, 1985; Piaget, 1952; Wellman & Gelman, 1988). Mandler (2000) summarized this problem when she wrote that “…one of the classic developmental dilemmas has been how to get from a nonconceptual organism that categorizes the world on the basis of what things look like to an organism that responds
on the basis of conceptually based processes” (p.19).

Nonetheless, although few would disagree that children by three or four years of age have acquired knowledge about the nonobservable properties of objects, whether this knowledge is fundamentally different to that acquired regarding perceptual properties during infancy, or whether it becomes the default basis by which to classify, remains under debate. It has recently been argued that the kind of dichotomizing portrayed by the notion of a “shift” from perceptual to conceptual categorization may oversimplify and mischaracterize representational change (e.g., Madole & Oakes, 1999; see Siegler, 1997, 2000, for an application of this argument to stage-based theories in general). In the same vein, it has been argued that no transition or shift need occur either because categorization relies on perceptual information throughout development (Eimas, 1994; Quinn & Eimas, 1997; Jones & Smith, 1993; Smith & Heise, 1992) or because categorization is conceptual from the outset, albeit based initially on perceptual information (Mandler, 2000). There are indeed further areas of ambiguity that stem from a more basic issue concerning the perceptual or conceptual status of different properties. Perceptual features are often characterized in terms of shape, color, texture, and so on, whereas nonobvious properties are often characterized as internal parts or structures or as functional attributes (e.g., possessing DNA, blood, a motor engine, the ability to fly). It is unclear, however, whether properties such as “chases mice” or “meows” are best thought of as perceptual or conceptual attributes of cats, or where the line exists between unambiguously perceptible properties, such as parts or size, and less perceptually available properties, such as “gives birth to kittens” or “has a heart” (Mandler, 1997; Madole & Oakes, 1999).

**Theses of the article**

In line with view of Eimas (1994; see also Jones & Smith, 1993), one of the main theses of this article is that the information incorporated into infants’ and children’s concepts is inherently perceptual in nature and that representational development occurs through gradual, incremental learning. That is, the properties of objects, even those that are not directly observable, enter the representational system and are encoded by one or more of the perceptual input systems. I propose that the nature of this information input process leads to the development of concepts that are intrinsically perceptual. Although this view is generally accepted when considering static properties that are readily perceptually available, in many cases it is assumed that nonobservable properties are fundamentally different either because they are only intermittently available in the perceptual array or because they must be learned through language or some other relatively indirect medium. For example, the functional property “can fly” is thought of as conceptual because one would not know that an object has such an ability solely from its appearance, and similarly the property “has a heart” is thought of as conceptual because one cannot easily see that an object or entity possesses such an organ and instead one must read or be told about it.

In contrast to these views, however, I propose that all of the properties of an object are perceptual in the sense that they can only become part of the concept for that object via the perceptual system: One might observe a plane or a bird fly or be told that people have hearts and there is no reason why this form of knowledge acquisition should be considered fundamentally different from that which occurs when one sees that a cat has whiskers or that a car has wheels. In many cases, the attributes commonly thought of as perceptual are not readily available in the input – for
instance, one cannot see a cat’s whiskers when it has its back turned – yet assumptions are made about the presence or absence of such attributes though inferential processes. Why then, is it necessary to take the position that properties that are generally unobservable – those labeled “conceptual” or “nonobvious” in the literature – are represented differently from those that are more readily perceived? I argue that this way of thinking emerged as a result of evidence showing that infants’ and preschoolers’ knowledge of unobservable properties takes precedence in category membership decisions (e.g., Gelman & Markman, 1986, 1987; Keil, 1989; Mandler, Bauer, & McDonough, 1991). It was implicitly assumed that if children tend to use one kind of information over another, there must be a qualitative difference between the two; yet there is no logical reason for such an assumption to be made.

A second, and related, thesis of this article is that infants represent objects and entities in the world in terms of clusters of correlated attributes. This idea is, in and of itself, nothing new. It is over twenty years since correlated attributes were posited as a significant organizing principle of categories (Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976; Rosch, 1978). More recently, Smith and Heise (1992) proposed that infants’ experience with correlations in the environment causes them to pay greater attention to the attributes that are a part of those correlations. In this way, infants move from an unstructured "similarity space" to a distorted or structured similarity space that is weighted toward particular features and correlations of features. Similarly, Madole and Oakes (1999; Madole & Cohen, 1995) proposed that older infants ignore arbitrary form-function correlations to which younger infants attend because their greater experience allows them to focus only on those correlations that are meaningful; for example, those in which form predicts function.

These previous formulations have suffered because, as pointed out by Keil and others (Keil, 1991, 1981; Murphy & Medin, 1985), the notion of correlated attributes as the foundation for representations is undermined by the same insufficiency of constraints as any other theory based on similarity; that is, there are so many correlations to which, in principle, one could attend that it is impossible to know which ones are important and which are illusory. A central argument of the proposal presented here is that it is possible, both in principle and in practice, to explain why infants attend to, and use as the basis for category coherence, certain correlations and at the same time ignore others. Although Madole and Oakes (1999) make a similar claim, they argue only that infants will show a familiarity preference to correlations that they have previously experienced. As an extension to this view, I posit that infants possess an associative learning mechanism and inherent attention biases - namely, sensitivity to movement, parts, and relative size - that allow for the detection and encoding of particular correlations among attributes, namely those that are dynamic, functional, and ultimately causal. It has previously been argued that people employ causal explanations to make sense, or deduce reasons, for correlations among features, and it is these lay theories that bind or structure concepts (Murphy & Medin, 1985). In contrast to this view, I will argue that theories about why features are correlated emerge only when such information is pertinent or in some way required. Certainly, children and adults expect certain features to co-occur; however, this does not mean that they necessarily have a lay theory for how and why such features are causally related, or that they need one in order
to have functional concepts for those correlations.

The outline of this paper is as follows: I will begin by describing the predominant theories of concept development in infancy; namely, the more conceptually-oriented approach of Jean Mandler (1992, 1998, 2000) and the perceptually-oriented approach of, among others, Peter Eimas and Paul Quinn (1994; Quinn & Eimas, 1997; also Jones & Smith, 1993). Although these theories differ considerably in their approach to the nature of conceptual structure and content, they overlap in their attempt to account for the early development of knowledge about the nonobvious properties of objects. I will argue that each approach, although capturing some aspect of the early conceptual development, is theoretically and empirically lacking. I will then present in more detail the theory that infants form object representations via an associative learning mechanism coupled with a sensitive perceptual system that is biased to attend to specific properties. Evidence from empirical studies with infants as well as that from connectionist models will be presented to support this view. Finally, I will discuss implications of the theory to cognitive development and cognition in general.

Theories of concept development in infancy
The role of nonobvious properties in early concepts

Despite a recent surge in interest in early category and concept formation, there is currently little agreement in the literature concerning the content of early concepts or the mechanisms underlying the development of infants’ and young children’s knowledge of objects in the world. Mandler (1992, 1998; 2000; Mandler et al., 1991), as part of one of the most comprehensive theories of concept development in the first two years of life, proposed that although the earliest categories are formed on the basis of perceptual prototypes, by 7 months of age infants begin to form conceptual categories. These conceptual categories are based on image-schemas, or conceptual primitives, which encapsulate crucial abstract characteristics of objects’ spatial structure and movement. For instance, animate objects are summarized by image schemas that represent self-motion, animate-motion (moving nonlinearly), causing action at a distance, and agency, whereas inanimate objects are summarized by image-schemas representing caused-motion, inanimate-motion (moving linearly), and caused to move through physical contact. Examples of how such image-schemas might be represented are shown in Figure 1 (taken from Mandler, 1992). According to Mandler (1992, 2000), these image-schemas are constructed through an innate process of perceptual analysis that recodes aspects of the perceptual display into a more abstract, accessible form that embodies some kind of meaning. Thus, Mandler (1992, 2000; see also Karmiloff-Smith, 1992) presents a stage-oriented theory whereby concepts undergo a radical change such that perceptual information is transformed into a conceptual format.

Evidence that is taken to support this view comes from research with sequential touching and object examining studies in which it was found that infants form categories with low within-category perceptual similarity – for example, animals, vehicles, or furniture (Mandler & Bauer, 1988; Mandler et al., 1991; Mandler & McDonough, 1998a) – and categorize as different perceptually similar items such as planes and birds (Mandler & McDonough, 1993). Infants in these studies also failed to categorize as different those objects that possess similar motion characteristics; for
example, dogs as different from horses or cars as different from trucks. Additional evidence to support Mandler's (1992, 1998, 2000) view is found in studies with the inductive generalization procedure in which infants are given a chance to repeat an observed action with a same or a different category member. Using this methodology, Mandler and McDonough (1996, 1998b) found that infants as young as 9 months generalize behaviors like drinking and sleeping to novel animals rather than to novel vehicles and behaviors like starting with a key and giving people rides to novel vehicles rather than to novel animals.

Mandler (2000) argued that these data provide convincing evidence that infants’ categories cohere because of nonperceptual information and that inductive generalizations are likewise based on knowledge about the nonobservable abilities, a view that is very much in line with the currently prevalent notion that nonobvious properties lie at the core of concepts (e.g., Gelman & Coley, 1990; Mandler, 1992, 2000; Murphy & Medin, 1985; Medin & Ortony, 1989; Keil, 1989). According to this view, surface properties are unstable and fallible guides for category membership and, more importantly, they are insufficient to represent the real nature – or essence (Medin & Ortony, 1989) – of things. Rather, it is proposed that people believe that deep, nonobvious properties make an object what it is, and their concepts embody theories that provide causes and relations among these properties and surface features. In this way, “perceptual features are constrained by and generated by the deeper more central parts of concepts” (Medin & Ortony, 1989, p.180).

Evidence that is taken to support the role of nonobvious properties in concept development tends to be drawn from experiments in which perceptual and nonperceptual information are pitted against each other. In one such program of research, children are asked to make inductions about objects based on information – a label, a line drawing, and a hidden property - they were given about another, target object. For instance, Gelman and colleagues (Davidson & Gelman, 1990; Gelman & Coley, 1990; Gelman & Markman, 1987) found that children as young as 2½ years of age made inductions to objects of the same category, (i.e., other snakes), even those that were perceptually dissimilar, rather than to perceptually similar objects from a different category (e.g., a worm). Using a different approach, Keil (1989; see also Rips, 1989) presented children with stories in which animate entities or inanimate objects underwent an appearance transformation but retained their nonobvious properties. In one such story, children were shown a picture of a raccoon and told that it possessed the blood, bones, and reproductive properties of a skunk. From around 4 years of age, children judged that in such cases it was the nonobvious properties rather than the perceptual appearance of things that determine what they are, or more specifically, how they should be labeled.

Arguments against the view of a nonobvious core

Mandler’s (1992, 1998) theory of conceptual development, and the more general notion that nonobvious properties are primary in concepts, has been the focus of considerable research and discussion in the developmental literature. The notion that objects’ motion patterns plays an important role in early concept formation is credible, particularly in light of evidence that infant are sensitive to movement almost from birth (e.g., Bertenthal, 1993; Slater, 1989) and that children and adults believe that motion is a fundamental criterion for judging unfamiliar entities as animate or inanimate (e.g., Richards & Siegler, 1986). There are,
however, a number of recent critiques to these approaches that need be delineated before their merit can be judged. On an empirical level, many researchers have noted difficulty with Mandler’s rich interpretation of her data (e.g., Jones & Smith, 1993; Müeller & Overton, 1998; Quinn & Eimas, 2000; Quinn, Johnson, Mareschal, Rakison, & Younger; 2000; Rakison & Butterworth, 1998a). It is far from obvious why it is necessary to posit that infants have early conceptual knowledge in order to explain the sequential touching, object examining, and generalized imitation data that Mandler presents (e.g., Mandler, Bauer, & McDonough, 1991; Mandler & McDonough, 1993, 1996, 1998). In many cases there is evidence that perceptual similarity can play the role ascribed to conceptual knowledge in such experiments: For example, infants as young as 3 months of age are capable of forming categorical representations - in a visual familiarization procedure - of mammals and furniture that include a host of perceptually diverse stimuli (Behl-Chadha, 1996; see also Younger & Fearing, 1999), and they are capable of forming a categorical representation for members of one class (e.g., cats) that excludes exemplars from a perceptually similar class (e.g., dogs) (Quinn, Eimas, & Rosenkrantz, 1993).

Furthermore, there is evidence from sequential touching studies by Rakison and Butterworth (1998a) that 14- to 18-month-old infants’ ability to form superordinate categories such as animals, vehicles, and furniture is affected considerably by the presence or absence of object parts such as legs and wheels. For example, infants categorize as different animals with legs and vehicles with wheels but they are unable to do so when the animals possess no legs and the vehicles possess no wheels or when both the animals and vehicles possess legs and wheels. There are also data to suggest that infants’ inductive generalizations in the task developed by Mandler and McDonough (1996, 1998b) may be guided more by perceptual similarity than knowledge about the specific actions of animates and inanimates. Using the same procedure as that the studies by Mandler and McDonough (1996, 1998b), Poulin-Dubois and Rakison (2000a) found that infants will repeat the observed actions with an inappropriate novel category member if the experimenter models the action with a prototypical inappropriate exemplar; for example, having seen a car go up a set of stairs, 14- and 18-month-olds will repeat the action with a novel vehicle rather than a novel animal.

At a more theoretical level, Mandler’s (1992, 1998, 2000) theory has been questioned for its failure to specify how the process of perceptual analysis – whereby information available in the perceptual array is translated into a simpler, conceptual image-schema - might operate. This process, which is the crux of Mandler’s stage-based theory, is as yet laid out only in general terms that fail to provide sufficient information to allow for a direct empirical test to be made. An additional problem with Mandler’s formulation is that as a consequence of the notion that there are distinct mechanisms that deal with perceptual and conceptual categorization, the appearance of objects is represented separately from their meaning. That is, “image schemas representing biological motion, self-motion, and contingent motion would be independent of the actually appearance of the movement of any particular object” (Mandler, 2000, p. 20). One cannot help but wonder whether it is necessary to posit such a dual-process framework when a single, integrated representational mechanism offers a more parsimonious and just as viable framework for concept development in infants and adults (Goldstone & Barsalou, 1998; Quinn et al., 2000). Finally, it is questionable whether the
process of perceptual analysis differs from perceptual categorization of movement patterns (Quinn & Eimas, 2000). There is no compelling reason why movement patterns of objects need to be abstracted in the way formulated by Mandler (1992, 2000): It is just as reasonable to suppose that these perceptually available patterns of movement are associated with individual exemplars, and then later are generalized to other category members.

The evidence that older children base their categorization and inductions on knowledge about nonperceptual properties has also come under scrutiny in recent years by Smith and her colleagues (e.g., Jones & Smith, 1993; Smith & Samuelson, 1997; Thelen & Smith, 1994). Jones and Smith (1993) argued that in studies like those conducted by Gelman, in which perceptual properties are pitted against category membership, perceptual aspects of the stimuli are impoverished compared to their real world appearance. This, in addition to the fact that the objects are typically labeled with familiar names – snake, worm, cat, skunk, for example – means that children have to make category induction either on the basis of nonobvious properties and a label or on the basis of a line drawing. Similarly, in the transformation studies by Keil (1989), children are presented with a line drawing and a considerable amount of information about the entity’s nonobvious properties. Perhaps children interpret this bias in the amount of information given as a suggestion that, in fact, the object is defined by its nonperceptual properties, and therefore they tend to choose nonobvious properties to decide what kind of thing something is. Indeed, there is evidence that children 8 years and younger will generalize a trait to a perceptually identical drawing rather than one with the same label (Farrar, Raney, & Boyer, 1992). Finally, Jones and Smith (1993) suggest that children and adults in the induction and transformation studies may use general knowledge about biology, the validity of stories, and even the psychology of experiments, rather than knowledge about skunks, raccoons, or worms per se. In other words, judgments about category membership in such tasks may be “assembled from multiple kinds of knowledge” that include perceptual, nonperceptual, linguistic and even social referents.

The role of perceptual properties in early concepts

In contrast to the view of infants as precocious concept formers, and the idea that nonobvious properties are at the core of concepts, a number of researchers have recently proposed that obvious, perceptual cues underlie early categorization and are the cornerstone of concepts. In particular, Quinn and Eimas (e.g., Eimas, 1994; Quinn & Eimas, 1996a, 1997, 2000) have posited that category coherence remains grounded in perceptual information during infancy and, perhaps, throughout the lifespan. They argue that the position that infants possess specialized representational processes such as perceptual analysis and specialized representational structures such as image-schemas is not only unparsimonious but it is not supported by the available empirical data (Quinn & Eimas, 2000). Instead, they believe that concept acquisition is a process of continuous representational enrichment that relies on a perceptual system that is sufficiently sensitive and robust to allow infants to form categories that cohere because of similarity relations. Thus, young infants categorize on the basis of object attributes such as for, example, shape and texture (e.g., Jones, Smith, & Landau, 1991; Jones & Smith, 1993), functional parts (e.g., Rakison & Cohen, 1999), or facial features (e.g., Quinn and Eimas, 1996b). The development of language allows the acquisition of
knowledge about the nonobservable characteristics of objects – in particular, biological functions like reproduction and other internal properties - through formal and informal tuition. In other words, language functions “as an input system that can serve as a rich source of information about objects that may not often, or even ever, be immediately apparent through looking, hearing, touching, and tasting” (Quinn & Eimas, 2000, p.57). This leads, ultimately, to a representation for animals that include shape, texture, facial features, and less obvious, nonobservable properties.

Quinn and Eimas also propose that infants acquire knowledge about the motion characteristics of objects – which are by many thought to be crucial in developing an animate-inanimate distinction (e.g., Mandler, 1992; Rakison & Poulin-Dubois, in press) - through continued perceptual categorization and association. Thus:

The common aspects of the features for animate things, for example, biological motion, that are found in the categorical representations for different species are presumed to be recognized and abstracted (categorized) for the basis for a representation for animate beings…. As a consequence, a number of properties, for example, locomotion and the possession of faces, legs, elongated bodies and so forth, may be individuated and represented by some average or prototypic value of range of permissible values. (Eimas, 1994, p. 87)

In other words, infants continuously add associative links between their earliest perceptual schemas and newly encountered information. For instance, infants may associate “chases mice” and “meows” with the perceptual category of cats, and ultimately this process will lead to the ability to form conceptually coherent categories that are based not on what something looks like but rather on what it is.

Arguments against the view of a perceptual core

Although the perceptually-oriented view of Quinn and Eimas has parsimony on its side – which in itself is not justification for their position - and is in agreement with a good deal of research on early categorization (e.g., Behl-Chadha, 1996; Quinn & Eimas, 1996b; Smith & Heise, 1992; Younger & Fearing, 1999), there are a number of problems with the similarity-based notion of enrichment. First, as with the criticism applied to similarity theories in general, it is not clear which properties of any given category will become associated with the perceptual schema for that category, nor which ones will be applied to form categories (e.g., Murphy & Medin, 1985). Quinn and Eimas (1996b) have shown that infants in the familiarization procedure are able to form categorical representations for cats that excludes dogs on the basis of facial features but not body information, yet this is not necessarily evidence that such features are used to categorize animals in the real world.

Second, it remains to be seen whether the continuous addition of associative links can function as a mechanism for representational change; that is, does such a process lead to conceptual knowledge – as formalized by Mandler, for example - or to ever more connected perceptual schemas or prototypes? Quinn and Eimas believe that the process of continuous representational enrichment can lead to the appearance of qualitative change in infants’ categorizing behavior, but it is as yet unspecified what kind of perceptually-based information, if any, needs to encountered before such a change can occur. Finally, the process of how such associations are formed has not been
formalized. For instance, Quinn and Eimas (2000) discuss how infants categorize animals by facial features, parts, shape, and so on, and that later these perceptual features become associated with self-starting movement patterns. However, they fail to specify in any detail how this associative process might work. In previous discussions of the role of correlated attributes on conceptual coherence, it has been suggested that features that are correlated are labeled and linked such that, for example, the features “has whiskers”, “chases mice” and “purr” might have arcs labeled CORRELATED between them (Smith & Medin, 1981). As pointed out by Murphy and Medin (1985), however, this idea suffers from computational intractability that would result from an explosion of links. They proposed instead that because correlations are not arbitrary, it is possible that causal explanations about why certain features are associated - based on general knowledge about the world – act as a binding agent to connect those features. Whether such an account can plausibly be applied to infants’ associations among features remains to be seen, however.

Summary of the perceptual and nonobvious core positions

Mandler’s (1992, 1998, 2000) and Quinn and Eimas’ (1996a, 1997; Eimas, 1994) theories of infant category and concept formation are clearly at odds. On the one hand, Mandler argues that infants are precocious concept formers in the sense that as early as 7 months they form categories that cohere not because of perceptual features but rather because of abstracted knowledge about the movement patterns of things. As part of this stage-based theory, it is posited that infants possess specialized processes and representational structures that facilitate the rapid acquisition of information about objects’ motion-related properties. In contrast to this view, Quinn and Eimas have proposed

that infants form perceptual prototypes for objects early in life and, over time, information is gradually associated with these prototypes. According to this view, which stresses the continuity of representational development, nonobvious information concerning motion characteristics is incorporated into concepts through a process of association and information concerning biological characteristics is added via language.

A correlation-based account of conceptual development

Both of the available theories of concept and category development have considerable merit yet suffer from their failure to account fully for the incorporation of nonobvious information into infants’ earlier representations. Although I agree with Mandler’s emphasis on the acquisition of the motion characteristics of objects, the empirical data do not support the idea that young infants possess the specialized representational processes or knowledge of nonobvious properties with which Mandler ascribes them. In addition, Mandler’s theory fails to take into account how infants learn about the psychological characteristics of objects such as goal-directedness or intentionality (see e.g., Rakison & Poulin-Dubois, in press). Likewise, although I support the perceptual enrichment stance presented by Quinn and Eimas, I am concerned that their theory does not adequately account for how nonobvious properties – in particular, motion- and psychological-related characteristics – become integrated into the representations for objects. The idea that infants form multiple mental associations for the properties of entities and objects is intuitively appealing and has some empirical support as concerns static perceptual cues (e.g., Younger & Cohen, 1986; Younger, 1993), but it remains to be seen specifically how such a process might
operate with regards to dynamic, motion-related properties. Most significantly, their proposal is open to the same criticisms laid upon earlier similarity-based theories in that it fails adequately to provide constraints on the properties that will be at the core of concepts or that will be used as the basis for category formation.

I propose a perceptually oriented account of concept development in infancy very much in the spirit of that put forward by Quinn and Eimas (1996a, 1997; Eimas, 1994) but which has as its focus the motion and psychological characteristics of animate entities and inanimate objects. I suggest that the qualitative changes observed in infants’ categorizing behavior (see Mandler, 1992, 2000; Quinn & Eimas, 1996a, 2000) come about as a result of the emerging sensitivity to, and gradual acquisition of, information about these domains of causal interaction through the perceptual input systems. The primary mechanism underlying this process is associative learning, by which I mean a domain general ability to encode relations among static and dynamic attributes available through one or more of the perceptual systems. Many agree that the ability to attend to clusters of correlated attributes is a fundamental early learning mechanism, yet thus far it has been considered mainly with regard to infants’ perception of static object features (e.g., Younger & Cohen, 1983, 1986, Younger, 1993). However, I claim that the same basic underlying learning mechanism is in place from early in infancy and what changes is the perceptual information to which the developing child becomes sensitive and able to represent. In other words, I argue that no “perceptual to conceptual” shift occurs because representations continue to develop through the acquisition of perceptual information, and this process is inherently gradual rather than stage-like. As discussed earlier, Quinn and Eimas (1996a, 1997; Eimas, 1994) have suggested that associative processes are responsible for infants’ ability to acquire knowledge about the motion properties of objects. My aim is to lay out in more detail how such associative learning might occur, how the acquired properties might be incorporated into early concepts, and how this gradual learning process might operate as a mechanism for conceptual change by enriching, in a quantitative rather than a qualitative sense, the representations already in place.

Before outlining the specifics of these processes, however, it is necessary to discuss certain abilities possessed by the newborn infant. In contrast to previous similarity-based theories, I propose that these abilities act as constraints, or attention biases, that help to guide infants’ learning of relevant perceptually available features and in so doing facilitate the acquisition of knowledge about objects’ physically- and psychologically-causal characteristics. This is not to say that infants have no other innate constraints that direct their attention not that constraints cannot be learned; however, I argue that the constraints outlined here have a profound effect on early learning about the different object kinds that exist in the world.

**Early attention biases**

Attention to movement. Perhaps the most important attention bias concerns the way that infants, as well as children and adults, find movement highly salient. It has been well documented that newborns prefer moving objects over static objects (Slater, 1989), that 4-month-olds’ perception of object unity for a partly occluded object depends on common motion (Kellman & Spelke, 1983; Needham, 1994), and that by 3 months of age infants prefer a human moving point-light display to an unstructured point-light display (Bertenthal, 1993). Indeed, motion cues continue to play an important role throughout the lifespan. There is evidence, for example,
that adults and infants detect an object’s properties more easily when it moves than when it is stationary (Burnham & Day, 1979; Washburn, 1993; Werker, Cohen, Lloyd, Casasola, & Stager, 1998), and that 4- and 7-year-olds as well as adults base their category judgments for animals on motion characteristics rather than shape when those two attributes are pitted against each other (Mak & Vera, 1999).

These studies suggest that infants have an innate predisposition to attend to motion, and the ability to perceive certain object characteristics are dependent on the presence of movement cues. In all likelihood, this sensitivity to object motion has evolved as part of a predator avoidance mechanism: Young vervets, for instance, rely solely on motion cues to categorize potential predators, and will initially make false “eagle” alarm calls for a whole host of birds and even quickly falling leaves (Evans & Marler, 1995; Seyfarth & Cheney, 1986). It must be borne in mind, however, that although the infancy studies cited above highlight an early attention bias to what can be thought of as movement at a local level – for instance, the hand and arm of a person who reaches for an object – this does not mean that they are necessarily able to discriminate between different instantiations of a particular movement characteristic. For example, infants might attend to the movement of a cat or a car from point A to point B but they would not, initially, be able to ascertain whether the motion path between the two points was smooth or irregular (see Rakison & Poulin-Dubois, in press). I argue that the gradual emergence of such a sensitivity, along with other similar developments within the perceptual and cognitive systems, is what allows infants to attend to and encode ever more complex and varied aspects of the perceptual array.

Attention to parts. A second proposed attention bias concerns the way in which infants, as with older children and adults, analyze objects into smaller parts and then later recombine those parts into wholes (e.g., Biederman, 1987, 1990; Cohen & Younger, 1984; Triesman, 1985, 1986; Slater, Mattock, Brown, Burnham, & Young, 1991). This ability to parse objects into their component parts not only makes it possible to interpret a three-dimensional world from a two-dimensional retinal image, but it also reveals the part structure of an image which in turn allows object recognition even when portions of an object are occluded. Indeed, recent psychophysical evidence revealed that the visual system parses shapes into parts preattentively (Baylis and Driver, 1995a, 1995b), which is consistent with the notion that infants process parts prior to processing wholes (Cohen, 1992; Werker et al., 1998); that is, they process individual attributes or object before they can form associations among those attributes or objects.

That part structure plays an important role in object recognition and categorization during infancy and throughout the lifespan is now well established. It has been shown, for example, that infants detect and categorize on the basis of correlations among attributes such as legs, heads, and tails as early as 7 months (e.g., Younger & Cohen, 1986; Younger, 1993) and that 14- and 18-month-olds’ ability to form animal- and vehicle-like groupings is determined by the presence or absence of common parts and common part structures (Rakison & Butterworth, 1998a, 1998b). In addition, Tversky (1989) found that not only do 5-year-old children make taxonomic groupings more readily when exemplars share parts, but also they detect missing parts faster when they are external, large, and affect shape (e.g., wheels) than when they do not affect shape (e.g., headlights). Finally, Palmer, Rosch, and Chase (1981) found that adults agree certain viewpoints of common objects are more informative, or canonical, than...
others, and the canonical viewpoints were those that showed the more important parts in contour.

**Attention to size.** The notion that objects have a canonical viewpoint ties in with an additional attention bias concerning the size of a part or object. That is, humans tend to find large parts (and large objects) more salient than small parts (and small objects). The terms large and small are used here to refer to relative size; thus, to use the formulation development by Hoffman and Singh (1997), the salience of a part tends to increase as the ratio of its visible area to the visible area of the whole silhouette increases. Although the effect of relative part size on infants’ ability to recognize objects has, to my knowledge, not been yet been tested, there is evidence that newborns are born with certain abilities specific to size and shape. For example, neonates show evidence of both shape and size constancy (Slater & Morrison, 1985), and when presented with two objects – for instance, two cubes – they prefer to look at the one that gives the largest retinal image (Slater, Mattock, & Brown, 1990). And as outlined in the preceding section, the size of a part affects how quickly children detect that it is absent (Tverky, 1989). It seems highly likely, therefore, that infants, as is the case for young children and adults, find larger parts more salient and revealing about an object’s structure and identity than smaller parts.

**Associative learning as a mechanism for conceptual change**

I posit that in the same way that infants’ associative learning mechanism allows them to represent correlations among the static perceptual attributes of category exemplars (e.g., Younger & Cohen, 1986), so they are also able to represent relations between those same attributes and the physical and psychological actions with which they are causally involved. These physically- and psychological-caused actions are all readily available in the perceptual array – even those that involve some inference about the mental states of others (see below) - and they correspond to the different kinds of abilities of animate entities and inanimate objects. The three attention biases outlined in the previous section are fundamental in this process in that they direct infants toward particular aspects of the perceptual array that are informative about the identity and characteristics of objects. That is, they draw attention to the movement of objects – both at a local and a global level - and the parts of objects, particularly those that are large and that move. In the case of mammals, for instance, it would be predicted that infants would attend to their global movement patterns – the trajectory of their motion, whether they start moving without outside force, and so on – as well as the large static and dynamic attributes they possess such as legs, tails, and facial features.

Attention to object parts is a crucial aspect of this learning process because in many cases biological parts have evolved with, or artifacts’ parts are specifically designed for, causal or functional significance. Infants predisposition to attend to object parts would therefore, in all likelihood, mean that they also perceive those parts engaging in some kind of functional activity. Moreover, the movement of the causally significant parts tends to coincide with the action with which they are connected; for instance, the legs of an animal or the wheels of a car are integrally involved in locomotion and it is during these actions, and generally not at other times, that such parts themselves are in motion. Similarly, arms often move toward an object when engaging in some kind of goal-directed action, and the fingers of the hand tend to open and close when an object is grasped and not at other times (Woodward, 1998, 1999). Tversky (1989) summarized succinctly this connection.
when she wrote that parts “seem to be simultaneously natural units of perception and natural units of function” (p.983).

According to Rakison and Poulin-Dubois (in press), infants must first discriminate between the animate and the inanimate appropriate action - for instance, they must distinguish self-propelled from caused motion – after which they can start to associate a particular action with a particular feature or object. The authors proposed these processes of discrimination and association occur for the following seven different causal actions – five of which concern physical relations and two of which concern psychological relations – during the development of a distinction between animate and inanimate things: (1) onset of motion (self-propelled versus caused motion), (2) line of trajectory (smooth versus irregular), (3) form of causal action (action at a distance versus action from contact), (4) pattern of interaction (contingent versus noncontingent), (5) type of causal role (agent versus recipient); (6) purpose of action (goal-directed versus without aim); and (7) influence of mental states (intentional versus accidental).

I argue that from around the middle of the first year of life infants start to form associations between static features of objects (e.g., Younger & Cohen, 1986), and they begin to form associations between relatively simple dynamic cues that they have repeatedly observed or that are given by some kind of naturally occurring, common amodal facilitating cue that qualifies a correlation; for instance, synchrony, pitch, and intensity are thought to facilitate young infants’ ability to associate words with objects (Gogate & Bahrick, 1998; Werker et al., 1998). It is not until between 10 and 14 months of age, however, that infants are more readily able to form associations between dynamic cues – largely due to an ever increasingly sensitive perceptual system and to general cognitive advances (e.g., greater memory capacity) - and it is at this point that these correlations become primary as a mechanism of conceptual change in the sense that learning about which attributes are involved in which of the causal actions described above is the initial development of what Mandler (1992, 2000) calls a meaning. This meaning, which emerges gradually as the strength of the represented relationship between an attribute and an action reaches some criterion level, is best thought of as an expectation rather than a sophisticated understanding concerning the abilities of objects or their parts. The resulting represented correlations need not be thought of as conceptual; instead, the perception of one component of the relationship activates an expectation about the existence of the other component (see Haith, Wentworth, & Canfield, 1993; Roberts, 1998). For instance, for young infants – say, those under 14 months – a feature such as “wings” would have no causal attribution associated with it but could nonetheless be used to classify birds or planes as different from dogs or cars; yet for older infants the same attribute would trigger knowledge about certain motion characteristics – among other things – such that the objects could be grouped together not only because they share features but also because they engage in similar motions (e.g., flying).

The idea that the represented association become strengthened over time – presumably through repeated experience with that association – implies that infants’ expectations about the presence of one component based on the presence of the other would take some time to appear. Although infants may have started to represent the relationship between an attribute and its causal role, there is probably a delay - during which other instances that possess the same correlation are encountered - before the strength of this association triggers an
expectation or allows a prediction to be made (see Munakata, McClelland, Johnson, & Siegler [1996] for a similar explanation of the A-not-B error). Nonetheless, once the association is sufficiently established, it is extended to include not only individual features but also whole objects - as is evidenced by the strong shape bias that appears in labeling and categorization toward the end of the second year (e.g., Baldwin, 1989; Imai, Gentner, & Uchida, 1994) - and ultimately whole categories of objects. Thus, infants might initially expect a particular attribute to be related to a particular action - for example, “things with legs walk” - then later they would expect a specific object or a category of objects to engage in that action; for example, “Mommy walks” or “things with legs, facial features, and tails walk”.

----------------------------------
Insert Figure 2 about here
----------------------------------

In many cases it is possible that by way of greater exposure infants learn about animate entities – namely, the attributes they posses and the actions in which those attributes engage - before they learn about inanimate objects. In particular, there is evidence that even infants may associate certain behaviors and mental states with people within the first six months of life (e.g., Bertenthal, 1993; Leslie, 1984; Poulin-Dubois, Lepage, & Ferland, 1996; Woodward, 1998, 1999). For example, the results of a study by Woodward (1998) implied that infant as young as 5 months of age identify goal-directed action with people, or more particularly, with human hands and arms. In line with the theory forwarded here, this could be explained by the fact that infants observe a human hand engaging in various actions a great number of times - notably during periods of play, comforting, or feeding – and they therefore come to associate it with behavior that has some kind of emotional or psychological causality. Moreover, the “like me” stance posited by Gopnik and Meltzoff (1993) – whereby infants recognize the similarity between people and themselves - can account for the early development of an understanding of the psychological causation. It may well be that infants notice the association between their intention to cause an act and that act’s occurrence (Piaget, 1952), and extend this association such that people are expected to have a similar underlying psychological drive.

It should be pointed out that there is overlap between the general position presented here and the notion of perceptual learning proposed by E. J. Gibson (1969; J. J. Gibson & E. J. Gibson, 1955). In particular, there are similarities between aspects of the present theory and the concepts of attention weighting, feature and stimulus imprinting, differentiation, and unitization (see Goldstone, 1997). Nonetheless, though the mechanisms posited by perceptual learning theorists are in some sense alike to those suggested in this article – for example, attention biases could be interpreted as the same as attention weighting – I propose a mechanism whereby infants’ perception of certain dynamic cues, and the expectations that emerge from the association of these cues, lead to a continual enrichment of object representations.

Figure 2 uses a similar schematic presentation to that developed by Mandler to illustrate the developmental progression in concept formation outlined above with respect to regular and irregular motion paths. It can be seen that a first phase of this process involves the discrimination of the instantiations of an animate and inanimate motion characteristic. Infants at this point must also be able to parse certain features from any given object, and presumably this process occurs first for those prototypical exemplars of superordinate domains – people, dogs, cats, cars, trucks,
chairs, and so on – with which infants have greater experience. During a second phase in the process, infants detect an association between a feature and the action with which it is causally related, and as more instances are encountered that exhibit this same relationship, the represented link between the feature and the action becomes stronger. As discussed above, it is often the case that inanimate objects do not possess moving, functional parts and therefore it is possible that associations between motion characteristics and animates are acquired by default and involve whole objects rather than a specific attribute. Irrespective, during the next phase in the process the represented association is strong to allow inferences about the features or abilities of an object based on the perception of one component, and it is generalized to include other features of the object including its overall shape. During a fourth phase of the process, the association is generalized from the members with which infants have had direct experience – cats, dogs, cars – to other less prototypical members of the category that possess certain characteristic features. In this way, it is not necessary for infants to experience each category member engaging in a particular action, nor is it necessary that particular features be observed to make a prediction about the ability of an object or entity to perform certain actions. Evidence to support this idea comes from a study by Massey and Gelman (1988) in which 3- and 4-year-olds were presented with static pictures and asked to judge whether an entity such as a man or a marmoset can go up and down a hill “all by itself”; the children’s explanatory comments for their decisions often focused on legs and feet, even if those features were not visible (Massey & Gelman, 1988); for example “It can move very slowly…it has these little legs” (Gelman, 1990, p.93).

The learning process illustrated above presumably occurs for each of the different roles played in a causal scene by animate entities and inanimate objects. As characterized in Figure 3, each one of these roles become associated with the representation for the category so that by the end of the second year infants have developed a considerable database of knowledge about the static features of various categories as well as the dynamic, causal roles that members of those categories are likely to play. This knowledge can still be broken down when necessary to specific instantiations or features of category members, as evidenced by the children in the study by Massey and Gelman (1988). However, as children become older so they are more likely to make inductions and inferences on the basis of category membership rather than specific associations between causal properties. For instance, if I observe an object flying along a nonlinear motion path, I do not need to see its parts to predict that it is a bird.

I posit that the role of language is crucial in the later stages of this process as it allow infants rapidly to learn information about objects, particularly that referred to as nonobvious information. As outlined earlier, I see no reason why linguistic input should be considered fundamentally different from that derived through, for instance, the visual system. In other words, labels for whole objects or the properties of those object become associated – in a similar manner to that described above - to the already established representation possessed by the young learner. However, it should be noted that one aspect of linguistic input contrasts it in an important way from that received from the visual, tactile, and auditory systems. Recall that with the kinds of concept formation discussed thus far, it was posited that the strength of the association increases as the number of exemplars that exhibit the
appropriate relationship are encountered. In the case of language, however, I claim that any given information concerning an attribute or property is assumed by the infant or young child to apply to all of the members of the category – depending on how category membership decisions are made at that age - as well as to those classes that are subsumed by the original category.

In other words, I wish to argue that linguistic input concerning an attribute or property is interpreted – after perhaps only one or two labeling events, as in the case of fast mapping (see Bloom, 2000 for a review) - as correlating perfectly with class membership such that all exemplars that are deemed members of the category are assumed also to possess that attribute or property. It is not necessary for infants to be told that each exemplar within the category of “dogs” possesses, for example, a heart. Instead, I suggest that infants generalize such an attribution to all those exemplars that are considered alike to the original referent, including perhaps those exemplars that lie within the same superordinate domain but that belong to a different basic-level category; for instance, “possesses a heart” might be extended also to cats, cows, people, and so on. Although admittedly speculative, such a position is consistent with the fact that infants tend to make overextension errors on the basis of perceptual or featural similarity (see e.g., Nelson, 1974; Rescorla, 1980), the tendency of attribution errors to continue until at least preschool age (Carey, 1985), and various proposed constraints that are specific to early word learning (see e.g., Markman, 1991).

Evidence to support the general position forwarded here can be found within (at least) two distinct programs of cognitive science: Namely, empirical data from studies with infants, and connectionist approaches to modeling cognition and cognitive development. I will briefly outline this evidence in the following sections.

Empirical data from experiments with infants.

As outlined earlier, there is considerable evidence that infants are sensitive to correlations among static attributes and will form categories based on these correlations within the first 7 months of life (Younger & Cohen, 1993, 1986; Younger, 1993). However, more crucial to the domain-general aspects of the theory presented here is evidence that infants are sensitive to dynamic cues and form associations among them within and across the sensory modalities. As one might expect given the relatively complex nature of motion related characteristics, the available empirical evidence suggests that although infants as young as 7 months can learn to associate an object with a vowel sound under certain facilitating conditions (Gogate & Bahrick, 1998), the ability to form associations among attributes that are not static appears in earnest at the beginning of the second year. For instance, evidence that infants between 10 and 14 months of age can form associative links between objects and labels came from a recent series of studies by Werker et al. (1998) with the Switch design in a habitation procedure (see Cohen, 1992; Younger & Cohen, 1986). Werker and her colleagues tested whether infants are able of form word-object associations both when objects move and when they do not move. Results of the experiments showed that 14-month-olds associate a label with an object but do so only when the object moves, whereas infants younger than 14 months failed to learn the label-word association but did process independently the attributes presented. Thus, there is support for the notion that early word comprehension may involve the development of an associative link in which a linguistic form is recognized and connected to a particular object and that movement is crucial in this process,
presumably because it acts to capture infants’ attention and increases the likelihood that an object’s properties will be examined (e.g., Oviatt, 1980, 1982; Werker et al., 1998).

Comparable evidence that infants between 14 and 18 months of age can form associations between two visual cues is found in a series of studies by Madole and her colleagues (Madole, Oakes, and Cohen, 1993; Madole and Cohen, 1995). Using the object-examination paradigm, Madole et al. (1993) familiarized 10-, 14-, and 18-month-old infants with a number of objects that either differed or correlated in form and function (e.g., rolling, shaking). The infants were then tested with a novel object that did not embody the properties of the training exemplars. Results showed that 10-month-olds attend to form, 14-month-olds attend to form and function as independent properties, and 18-month-olds attend to the relation between an object’s form and its function. These data were confirmed in a second series of studies by Madole and Cohen (1995) in which infants were again taught form-function correlations but rather than the whole object embodying the functional property it was characterized by a moving parts such as wheels or a tree-shape that rotated. Using this design, it was found that 14-month-olds could correlate the form of an object – that is, one of its moving parts - with a functional property.

In order to examine the more specific theory that infants are constrained to form associations between functional object parts and motion characteristics, and then generalize this association to whole objects, I have recently used a variation of the Switch design in a series of experiments with 10- to 18-month-old infants (Rakison & Poulin-Dubois, 2000). During the habituation phase of these experiments, infants were presented with two events in which a geometric figure moved across a screen. Each figure had a distinctive set of moving parts (horizontally moving green diamond shapes or vertically moving yellow cigar shapes), a distinctive body (blue, rectangular shaped or red, oval shaped), and a distinctive motion trajectory as it traveled across the screen (rectilinear or curvilinear). In the test phase, infants were presented with four events, three of which contained a change in the parts, the body, or the motion of the object, and the fourth of which was identical to that seen during habituation. With this design, it is possible to examine whether, as predicted, infants are biased to attend to certain associations rather than others; that is, infants could have learned the relationship between the parts and body of an object, the parts and motion of an object, the body and parts of an object, or the parts, body, and motion of an object.

The results of the experiment supported the hypothesis that infants initially associate the trajectory of an object with dynamic, moving parts and then later associate the trajectory with whole objects. At 10 months of age infants looked equally long at all four test events suggesting that they failed to associate the various attributes in the event, but at 14 months they looked longer at the part test trial - in which the part-motion path correlation was violated - than at the familiar event but not significantly longer at the other test events than at the familiar event. At 18 months, infants looked reliably longer to all three novel test events, which implied that they had connected the three attributes. In a follow up experiment designed to examine the facilitating effect of part movement, 14- and 18-month-olds were habituated to the events used in the first experiment, except that the parts no longer moved as the object traveled across the screen. Infants’ looking times in the experiment revealed that at 14 months they failed to form an association among any of the attributes in the events but at 18 months they formed an association between parts and motion path but not
between any of the other attribute correlations available in the events.

The results of these experiments are consistent with different aspects of the theory proposed in the current manuscript. First, the data support the idea that infants initially process the attributes of an event independently, then they form association between specific attributes – namely, those that are dynamic such as moving parts and a motion property – and even later still they form associations between whole objects and motions properties. Second, the fact that 18-month-olds are able to form an association between an object’s parts and its motion path when the parts do not move and that 14-month-olds are unable to, suggests that the initial strength of the representation between two dynamic attributes is insufficient to allow for prediction concerning the presence of one attribute based on the perception of another attribute. That is, by 18 months of age infants have learned about the causal relation between parts and motion characteristics, and they therefore expected the parts of the objects to be the attribute correlated with the linear or curvilinear motion paths in the events. In contrast, 14-month-olds may have started to form associations between parts and motions yet the strength of the association between these attributes is not yet sufficient to allow for such inferences to be made. Third, and most importantly, these studies demonstrate that infants can learn about the properties of objects that are classically thought of as nonobvious – in this case, trajectory of movement - by forming associations between those properties and the attributes that are causally involved with them. The resulting association allows for prediction and inference to be made such that the presence of one cue triggers retrieval of the memory trace for the other cue. Hence, if an infant learns the association between, for example, wings and flying, they could observe an object with wings and would expect that it could fly or they could observe an object flying and would expect that it possesses wings.

There is, therefore, evidence from a range of empirical experiments that infants are adept at detecting and learning about associations among static and dynamic attributes, that they can do so across the sensory modalities, and that there is consistency in the age at which this ability is found to develop: By 7 months or so infants are able to correlate static attributes, and they can correlate dynamic cues following repeated exposure to those cues – as is the case of the actions of human hands (Woodward, 1998, 1999) - or in the presence of one or more facilitating cues (Gogate & Bahrick, 1998); By 10 months, infants are generally unable to associate dynamic cues, though they are adept at processing independently such cues; and around 14 to 18 months of age they are able to correlate dynamic and static attributes. Interestingly, there appears to be a similar developmental progression for the ability to process static and dynamic cues. Younger and Cohen (1986) found that 4-month-olds process independently the features of an animal line drawing, 7-month-olds process relations among features but only for a single pattern, and 10-month-olds process relations among features even when embedded in a category (Younger & Cohen, 1986). Likewise, in the studies by Werker et al. (1998), Madole and colleagues (Madole et al., 1993; Madole & Cohen, 1995), and Rakison and Poulin-Dubois (2000), 10-month-olds were found to process attributes independently and 14-month-olds were found to process relations among those attributes. It remains to be seen whether these similar developmental trends are the result of comparable advances in cognitive processing during the 4 to 10 month and 10 to 14 month age range, or whether they reflect the gradual learning process that occurs
as relevant information is encountered by the infant. In part to answer this question, current studies in my lab are examining the age at which infants develop the ability to process dynamic relations among features that are embedded in a category. Evidence of associative learning in connectionist models.

Connectionist models are networks of simple parallel computing elements, or units, that are connected together by weighted communication lines. Each unit influences other elements through these lines such that the influence of one unit on another is calculated by multiplying its activation value by the strength of the connection between the two units. Those units that receive input from outside the network are known as input units, those units that transmit the state of the network are known as output units, and those units that are inside the network are known as hidden units. These hidden units can be thought of as an internal representation of the input; in the case of one kind of network architecture, known as an autoassociative or autoencoder configuration, the number of hidden units is smaller than the number of input or output units which means that information is compressed for the internal representation but still maintains sufficient aspects of the original input to allow for an appropriate – that is, correct - output to be made (e.g., Mareschal & French, 2000; Solokov, 1963). Crucially, the network learns gradually, following repeated exposure to a set of stimuli, by adjusting the connection weights between different units until the output units produce a certain value following a particular input.

In contrast to previous work on artificial intelligence systems, the massively parallel computation within a connectionist network leads to nonlinear responses by the units. This is, in part, why it is possible to draw interesting parallels between connectionist networks and cognitive development; namely, connectionist networks “develop their own task-appropriate internal representations as part of the learning process” (Mareschal & French, 2000, p.62). Moreover, representations are continuous and graded (Elman, Bates, Johnson, Karmiloff-Smith, Parisi, & Plunkett, 1997; c.f., Pinker & Prince, 1989), and as a result of this incremental learning often exhibit stage-like transitions in behavior (Elman et al., 1997; McClelland, 1989; Plunkett, Sinha, Möller, & Strandsby, 1992); that is, simple interactions at the local level often give rise to more complex global changes. Of particular relevance to the theory described in the present manuscript is that connectionist learning systems involve a form of associative competition akin to that found in synaptic connections (Siegler, 1989). Connections that are active are preserved and those that are inactive are curtailed. Within such a network, representations can therefore be thought of as patterns of activations over units in a layered system – which in turn is dependent on the patterns of weighted connections between units – just as in a real brain representations are fine-grained patterns of cortical activity based on specific patterns of syntactic connectivity (Elman et al., 1997).

Thus, connectionist networks seem to embody many of the properties of the representational structure and content that have been proposed in this manuscript. They learn gradually and exhibit large-scale stage-like changes based on this continuous process. Furthermore, information is represented, to some extent, in the form of associations such that if one unit is activated it is likely to activate the other units to which it has a strong connecting weight. In this way, a connectionist network is an excellent example of Hebbian learning in that is highly adept at representing correlations. As Elman et al. (1997) put it: “…the network weights are
changed according to the correlated activity
between nodes which are receiving input from
the environment. None of that input need be
instructive in any direct sense; the network
may be thought of as more or less passively
experiencing the environment and striving to
discover correlations in the input” (p.82).
Indeed, Hebbian learning has been the
underlying mechanism in models of, among
other things, object detection (O’Reilly &
McClelland, 1992), the detection of dilation
and rotation (Sereno & Sereno, 1991), and
syntactic pruning (Kerszberg, Dehaene, &
Changeux, 1992). This is not to say that all
learning is Hebbian; for example, the Hebb
rule cannot account for how patterns become
associated that are not pair-wise correlated.
Nonetheless, Hebbian learning appears to be a
fundamental mechanism for representing
information, and it does so primarily on the
basis of correlated activity.

In the last few years, researchers have
attempted to test predictions about early infant
categorization with the kind of connectionist
learning systems described above. Notably,
these researchers are predominantly those
with a perceptually oriented view of
categorization (e.g., Quinn & Johnson, 1996,
1997, 2000; Mareschal & French, 2000;
Mareschal, French, & Quinn, in press). In a
study of the development of basic- and global-
level categories in connectionist networks,
Quinn and Johnson (1996, 1997, 2000) used
the different attributes of mammals and
furniture – taken from pictures used in the
studies by Behl-Chadha (1996) - as input for a
simple three-layered (input-hidden-output)
network taught by a backpropogation learning
algorithm. Consistent with the global-to-basic
trend observed by Mandler and her colleagues
(Mandler et al., 1991; Mandler & Bauer,
1988), the network formed global categories
of mammals and furniture before it formed
basic-level categories such as cats, dogs, or
tables.

The studies by Quinn and Johnson
(1996, 2000) demonstrate that connectionist
models can provide a reasonable simulation of
the global-to-basic trend in early infant
categorization. As Mandler (2000) has
pointed out, however, in many cases the
categorization of, say, animals from furniture
could have been accomplished by the network
on the basis of presence versus absence of a
single attribute; for example, facial features
versus no facial features. Mareschal, French,
and Quinn (in press) present perhaps an even
more impressive demonstration of the
similarity between infant categorization and
the associative learning mechanism of a
connectionist network which cannot be
explained by attention to a single attribute. In
the simulation, the authors attempted to model
the asymmetric category learning by 3- and 4-
month-olds whereby infants familiarized to
various cats preferred to look at a novel dog
over a novel cat but infants familiarized to
various dogs did not show a preference for a
novel cat over a novel dog (Quinn et al.,
1993). The connectionist simulation, when
presented with attribute values representing
the stimuli used by Quinn et al. (1993),
exhibited the same asymmetric category
learning as that observed in young infants.
The authors concluded that such asymmetries
emerge from an interaction between the
statistics of the feature distributions in the
stimuli (attribute value-wise, a cat is more
likely to be a dog than a dog is likely to be a
cat), the distributed internal representation,
and the associative learning of the network
(Mareschal et al., in press).

Perhaps even more pertinent to the
present manuscript is recent work by
Mareschal and colleagues (Mareschal &
French, 2000; Schafer & Mareschal, in press)
that explored how connectionist networks
might extract correlations from the input.
Mareschal and French (2000) attempted to
model in simple autoencoder networks 10-
month-olds’ ability to form categories based on correlated attributes. The authors used attribute values from artificial animal-like stimuli generated by Younger (1985) and presented separate networks with one of two sets of stimuli: In the broad condition, any feature could co-occur with any other feature, and in the narrow condition, certain features tended to covary with each other. For these simulations, the level of error within the network for each stimulus during the test phase is equated with the looking time of infants during the test phase of familiarization studies; thus, high error terms are considered to be comparable to long looking times by infants. Results of the simulations revealed that, as with 10-month-olds in Younger’s (1985, Exp. 1) study, the network trained with the broad set of stimuli responded as if they formed a single representation for the category whereas the network trained with the narrow set of stimuli responded as if they formed two distinct categories on the basis of feature covariation.

Finally, recent work by Schafer and Mareschal (in press) provides a relevant demonstration that continuous, gradual learning within a simple associative mechanism can lead to qualitative changes in behavior. Using a simple connectionist autoencoder network, Mareschal and Schafer (in press) attempted to model the results of Stager and Werker (1997) who, with the same general methodology as that used by Werker et al. (1998), found that 8-month-olds in a label-object associative learning task discriminated two similar phonemes (bih-dih) and that 14-month-olds were unable to do discriminate those same phonemes but could discriminate two relatively distinct ones (li-fi-neem). Stager and Werker (1997) interpreted these results to mean that infants apply different processing mechanisms to the same stimuli at 8 and at 14 months. That is, older infants process word-label pairs phonemically whereas younger infants process word-label pairs phonetically in that they are learning about the sounds of words. In an attempt to test this theory, Schaffer and Mareschal (in press) allowed connectionist networks to experience an artificial language, and then tested the networks’ ability to learn specific label-object pairs. As an analogy for the greater experience older infants have with words and objects in comparison to younger infants, “older” networks were exposed to more examples of the artificial language than “younger” networks. The results of the simulation matched impressively those found with infants by Stager and Werker (1997): “Younger” networks discriminated similar phonemes more easily than “older” networks, though the “older” networks were able to discriminate the dissimilar phonemes. What is particularly striking about these results is that the model provided a close fit to the behavior of infants – the qualitative changes in performance between the “old” and the “young” networks - yet a single associative learning mechanism was involved.

The connectionist simulations described in here provide direct support for the idea that early classification may rely solely on perceptually available cues, or as Smith (2000) put it, they “serve as a knock-down demonstration of the viability of perceptual similarity as the basis of infant categorization” (p.93). In particular, Quinn and Johnson (2000) demonstrate that the classification of global domains such as animals and furniture can occur in the absence of any conceptual information, and in conjunction with the work of Schafer and Mareschal (in press) show that continuous incremental learning can lead to changes in representational content. That having been said, these studies reveal only that connectionist networks are capable of extracting correlations among attributes - which is in part not surprising given that such
networks are based on a Hebbian form of associative learning – and not that they are sensitive to certain clusters of correlations and not to others. Moreover, as Mareschal and French (2000; see also Mandler, 2000) point out, their simulations do not provide insight into the development of the ability to attend to, and categorize on the basis of, correlations of features as highlighted in the studies by Younger and Cohen (1986).

It is not difficult to envisage how such problems could be overcome in future simulations. There are a number of ways to build constraints into connectionist networks akin to those thought to be present in the human brain. For instance, representational constraints that would bias a network to focus on certain attributes or attribute correlations could be implemented by setting prespecified weights on the inter-unit connections. Likewise, chronotopic constraints that would help to specify the developmental course of learning could be implemented by allowing the incremental presentation of data, by setting adaptive learning rates, or by cell division within the developing network (Elman et al., 1997). An alternative possibility is to create separate modules within the network that process particular kinds of information. For example, in an attempt to model young infants’ behavior in studies of object continuity, Mareschal and Johnson (2000) created four connectionist networks that included a number of neurally plausible information processing modules that separately processed the perceptually different cues available during an occlusion event. Thus, each module was designed to identify the presence or absence of one of the following cues: motion, texture deletion and accretion, t-junctions, co-motion (i.e., simultaneous motion) in the upper and lower halves of the retina, common motion in the upper and lower halves of the retina, co-linearity of objects in the upper and lower halves of the retina, and the relatability of objects in the upper and lower halves of the retina (i.e., whether the edges of objects would meet if extended behind an occluder). Following exposure to a simulated visual environment, all four of the models perceived a partly occluded object as unified. Thus, it is possible design and test a connectionist simulation with built-in processing biases, and the available evidence suggests that this approach might well prove fruitful in the future. Nonetheless, to create such a model a number of assumptions must be made about the internal mental processes involved, and care must be taken to keep these assumptions limited to relatively parsimonious, neurally plausible implementations of the constraints found in infants.

Summary and implications

In this article, I have argued that infants’ concepts of objects in the world – namely, animates and inanimates - develop through a process of continual representational enrichment. Fundamental to this process is that infants possess a sensitive perceptual system, which is biased to attend to particular aspects of the visual array, and a domain general associative learning mechanism, which detects and encodes correlations among static and dynamic attributes. As the perceptual system increases in sensitivity, and as the associative learning mechanism becomes more adept at extracting correlations, so infants are able to attend to more complex and varied information. Thus, infants’ earliest categories cohere by way of individual surface features - most likely overall shape and object parts - and then later, around 7 months of age, they begin to cohere because of correlations among those static features and, under certain conditions, because of correlations among dynamic features. Between 10 and 14 months of age, infants become sensitive to dynamic cues and...
correlations among those cues, which then become primary in category coherence.

In his way, infants’ categories appear to change qualitatively in the second years of life, though the underlying process of conceptual change is that of gradual, incremental learning of perceptual information (see also Eimas, 1994). Of key importance to the development of such concepts is that infants are biased to attend to particular attributes and associations among attributes. Unlike previous similarity-based formulations, I argue that there are constraints within the infant that facilitate attention to, and learning of, clusters of causally relevant correlated attributes that exist naturally among category members. To support this view of early representational development, I have presented evidence from empirical studies on infants’ ability to attend to static and dynamic correlations as well as recent connectionist simulations of early categorization. The empirical evidence provides a direct demonstration that infants develop the ability to detect and learn the associations that exist among specific features – namely, object parts and the functional or motion-related properties to which they are causally related – and the connectionist models suggest, among other things, that a form of continuous Hebbian-based learning can lead to qualitative changes in representational content and structure.

Early concept development need not, therefore, be seen in terms of a stage-like perceptual-to-conceptual shift. Rather, perceptual information continues to play a fundamental role throughout infancy, and presumably throughout the lifespan, and what changes is the information to which the ever-developing learner becomes sensitive and able to represent. It is not clear at the present time what underlies these changes in processing ability. One possibility is that the static, perceptual cues are acquired first because they are relatively invariant and easier to process than dynamic cues. On the other hand, it is also possible that some form of bootstrapping occurs whereby infants are able to represent associations involving dynamic features only after they have first represented static features. Finally, it is plausible that advances in more general processing abilities such as memory or encoding allow infants to incorporate ever more detailed and complex features of objects to be incorporated into their developing representation.

The same perceptually-based learning mechanism outlined in this article here can also be applied to the results of studies that reveal a precocious infant conceptualizer with respect to physical principles such as solidity, support, and gravity (e.g., Baillargeon, 1993, 1995, 1999; Spelke, Breinlinger, Macomber, & Jacobson, 1992). In general, these studies reveal that infants in the habituation paradigm act with “surprise” — that is, look relatively long — at events that violate physical principles, such as when a ball stops in mid-air rather than hitting the ground. In many cases, such results are taken to mean that infants possess innate mechanisms for interpreting events that involve fundamental physical laws (for an excellent discussion of this issue see Baillargeon [1999] and the accompanying commentaries). Without exception, however, these physical principles exemplify invariant associations available in the perceptual input with which even young infants would have had a great deal of experience. I believe that a learning-oriented, perceptually-based explanation for infants’ behavior to such violations of physical laws is not only parsimonious but also fits well the available data. For example, recent evidence that shows that infants’ notion of support is refined over the first few months of life is consistent with the idea of experience-based learning (Baillargeon, 1999). Likewise, to return to the example of gravity, having seen
falling objects on a number of occasions, infants would be expected to start to associate “objects without any obvious support” with “movement that continues until it reaches a flat surface”.

An additional implication of the current article is that the performance of children beyond the first two years of life needs to be re-evaluated. It has generally been assumed that nonobvious properties such as “has blood” or “is alive” are primary in category coherence during early childhood because they are chosen over perceptual features such as shape when the two are pitted against each other (e.g., Gelman & Markman, 1986, 1987). I have argued that properties commonly thought of as nonobvious are not represented in a qualitatively different way from those that are considered perceptual. Instead, the claim here is that the learning process involved is the same for both, though different input systems – namely, the visual system and the linguistic system - may play particularly dominant roles in the acquisition of each kind of information. It may well be that nonobvious attributes, which can be considered perceptual in the sense that they are learned via one of the sensory modalities, are primary in the kinds of studies mentioned above because they are perfectly correlated with category membership whereas other, more surface attributes are less so. For instance, all birds have bird DNA but not all birds can fly. This is not to say, however, that the categories that children and adults form in the real world will cohere because of such “nonobvious” properties; after all, if something has wings and feathers it is a pretty good bet that it is a bird. But in studies where two attributes are pitted against each other – irrespective of the methodological issues discussed earlier - it is perhaps not surprising that children might favor the one that is more invariantly associated with category membership.

In contrast to the widely accepted view that people employ causal explanations to make sense of correlations among features (e.g., Medin & Ortony, 1989; Murphy & Medin, 1985), I propose that it is the associations between properties and causal features formed during infancy that bind or structure concepts. Lay theories, I wish to argue, are later attached to these associations either during formal learning or as and when needed. In many cases, adults know that two features are correlated but they may have no understanding of the causal relation between those two features, nor need they develop some kind of lay theory to explain it in order to possess a functional concept. For example, I know that the computer I am working on, as with all computers, has some kind of silicon chips inside it, but I have not attempted to develop an explanation for how the chips make the computer function, though I could develop such a theory on-line if one were needed for some reason. Similarly, Smith and Samuelson (1997; see also Smith, 2000) have argued that the model for all cognition is the dynamic creation of a moment of knowing out of previous moments of knowing. This is not to say, however, that the view presented here is completely at odd with the idea that theories help to provide categories coherence. For instance, Murphy and Medin (1985) argued that “Concepts that have their features connected by structure-function relationships or by causal schemata of one sort or another will be more coherent than those that do not” (Murphy & Medin, 1985). My claim is that the causal link between attributes is inherent in the association between them that is formed early on in life, and when lay theories are developed to explain this causal link they will act to bind or cohere further the concept.

In summary, in this article I have presented a perceptually oriented theory of concept development in infancy. At the heart of this theory is the idea that infants possess a
sensitive perceptual system and an associative learning mechanism, which in tandem with certain innate attention biases, allow infants to form correlation-based representations of objects in the world around them. I argue that it is erroneous to think of representational development as undergoing some kind of transitional shift. Rather, perceptual information provided by the different sensory input systems – including language - is continually added to the infants’ current representations in the form of associations, and as sensitivity to different sorts of information emerges, so this gradual process gives the appearance of qualitative, representational change. The available evidence goes some way to support this position, though clearly further research is needed to substantiate the claims made here. Nonetheless, the theory posited here is very much in line with current thinking in early cognition that stresses an infant who is reliant on information available in the perceptual array and uses that information during category and concept formation (e.g., Eimas, 1994; Jones & Smith, 1993; Mareschal & French, 2000; Quinn & Eimas, 1996; Younger & Fearing, 1999, 2000). The connectionist simulations are particularly helpful in this domain because they allow infancy researchers not only to make tests of early conceptual content throughout the learning process but also to make some headway regarding the nature of conceptual structure. Advances in our knowledge of early development made from these simulations, in parallel with data from more traditional empirical methods, are starting to suggest that the seemingly intractable question of “What makes a category cohere?” is not so intractable after all.
References


Baylis, G. C., & Driver, J. (1995a). One-sided edge assignment in vision. I. Figure-ground segmentation and attention to objects. Current Directions in Psychological Science, 4, 140-146.


complex input output functions in neural clusters formed by synapse selection. *Neural Networks*, 5, 303-413.


Acquisition of word-object associations by 14-month-old infants. Developmental Psychology, 34, 1289-1309.


Figure 1. Examples of Mandler’s (1992) image schemas for animate, inanimate, and self-starting animate motion

Animate motion

Inanimate motion

Self-moving animate
Figure 2. Example of how associative processes extend from single features to categories

Discrimination of curvilinear versus rectilinear motion path

Association of causal feature (legs) with curvilinear motion path

Association of whole object and other features (e.g., tail, facial features) with curvilinear motion path

Association of category (e.g., animals) with curvilinear motion path
Figure 3. Example of concept for animal and its motion- and psychological-related characteristics.

Note: Filled circle denotes identity of category member in causal action.