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TARGET ARTICLE AND INVITED COMMENTARIES

How to Identify a Domain-General Learning Mechanism When You See One

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A longstanding and fundamental debate in developmental science is whether knowledge is acquired through domain-specific or domain-general mechanisms. To date, there exists no tool to determine whether experimental data support one theoretical approach or the other. In this article, we argue that the U- and N-shaped curves found in a number of studies across a range of developmental areas are a product of domain-general learning. This pattern arises through a combination of improving cognitive capacities, which allow for different levels of processing, and emergent constraints on learning. We propose that developmental scientists' knowledge of the meaning of this pattern can aid the theoretical interpretation of data as well as experimental design to incorporate a sufficiently inclusive range of ages.

One of the most enduring and challenging issues addressed by developmental science is to discover the origins and nature of knowledge. The Greek philosophers first debated this epistemological issue more than 2,000 years ago, and their disparate perspectives continue today. On the one hand, there are those who argue that infants develop knowledge—that is, form *concepts* or *mental representations*—via domain-specific learning mechanisms (e.g., Baillargeon,

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2001; Gelman, 1990; Leslie, 1995; Mandler, 1992; Premack, 1990; Spelke, Breinlinger, Macomber, & Jacobson, 1992; Wynn, 1992; Xu & Garcia, 2008). We use the term *domain-specific mechanism* here to refer to processes that are dedicated to learning about a particular area of knowledge (e.g., animacy, math, physics) and that may include certain rules or constraints that are present at birth or shortly thereafter.

These specialized mechanisms may operate for one or a range of inputs (e.g., auditory, visual, tactile), but because they putatively evolved to solve a specific adaptive problem, they process information about a single realm of knowledge and no others. Thus, just as the liver is a specialized mechanism that evolved to process toxin extraction, so specialized brain mechanisms are proposed to process only specific kinds of information. Leslie (1995), for example, posited that infants possess separate specialized modules, each of which processes different kinds of information about the properties of animates and inanimates. Thus, the theory-of-body module processes only physical information about objects, whereas the theory-of-mind module processes only psychological information about them. One implication of these kinds of domain-specific learning mechanisms is that they allow even very young infants to form rich, abstract concepts (e.g., animals are causal, goal-directed agents). It has yet to be determined, however, where one domain ends and another begins or how some domain-specific mechanisms but not others are "triggered" by the same input. For instance, learning about the movement of animates and inanimates encompasses the domains of both animacy and physics, and it is unclear how information from a motion event is channeled to the appropriate domain-specific mechanism.

On the other hand, it has been proposed that infants acquire knowledge via domain-general learning mechanisms such as habituation, conditioning, imitation, and associative learning (Madole & Oakes, 1999; Quinn & Eimas, 1997; Rakison & Lupyan, 2008; Rogers & McClelland, 2004; Smith, Jones, & Landau, 1996). The term *domain-general mechanism* is used here to refer to processes that are both knowledge universal and modality universal in that the same mechanisms function across a wide range of knowledge areas and inputs. Thus, just as each domain-specific mechanism processes input only for a specific domain of knowledge, so each domain-general mechanism is capable of processing comparably structured input that relates to any domain of knowledge. Infants, for example, habituate to sounds, visual images, and tactile input and can acquire knowledge about animacy cues, language, math, and physics from this type of learning. At the same, however, although these general mechanisms are powerful for extracting regularities that exist in the environment, they lead to relatively slow concept acquisition.

Typically, domain-specific mechanisms are formulated as innate and are either present at birth or triggered at some point in development. (We will discuss later the claim that domain specificity can emerge from domain-general learning when an individual has sufficient exposure to information about a specific domain.) In contrast, domain-general mechanisms are framed with respect to early learning and experience without prior constraints. However, we do not seek to reduce the domain-specific versus domain-general debate to a nature versus nurture debate, because both mechanisms involve learning processes to varying extents. Instead, we are interested in investigating the different learning trends that arise as a result of these mechanisms.

Why, despite the emergence of a large database on early learning, is there so little consensus about the mechanisms that underpin infants' knowledge acquisition? In our view, the main reason for the fractious nature of the ongoing debate is that there are no rules or guidelines for identifying whether early learning is grounded in domain-specific or domain-general mechanisms. That is, developmental scientists apply their theoretical perspective in interpreting data rather than rely on established and agreed-on principles for whether those data provide evidence for domain-general or domain-specific learning. For example, it was previously assumed that if an ability or knowledge is present early in life then these expectations must be innate or guided by domain-specific mechanisms (see e.g., Baillargeon, 1999; cf., Haith, 1998). However, clearly, this assumption logically is flawed because 5-month-olds have had 5 months to learn about physical events for which they display knowledge. Indeed, even newborns have had some in-utero sensory experience, which could have shaped their expectations. Likewise, it has been proposed that if infants' knowledge matches the input to which they are exposed, then this implies that learning is underpinned by domain-general mechanisms. However, there is no reason why the same prediction about a world-to-representation mapping could not be made from a domain-specific perspective.

What is needed, then, is a way of identifying patterns of behavior that are indicative of domain-general or domain-specific behavior. We offer one such indicator here. Note, however, that our goal is not to push for one theoretical perspective over the other. Instead, our aim is to provide developmental scientists with a tool that will help to interpret data correctly within a theoretical framework.

A PROPOSED MARKER OF DOMAIN-GENERAL LEARNING

The central thesis of this article is that a particular developmental trend that has been observed in infants and young children may be an indicator of domain-general learning. This trend has been sometimes labeled a U-shaped curve, which is typified by the pattern that younger children perform relatively well on a task, but then performance declines with age and then improves again at a later age. We propose here, however, that in many cases it is more accurate to label this trend an N-shaped curve because there is also an earlier period of developmental time during which children are unable to complete a task at all (see also Cashon & Cohen, 2004).

One example of this N-shaped trend was found by Rakison (2005), who examined when and how infants associate static and dynamic object features with the role of agency and recipiency in a causal event (see Figure 1). Rakison (2005) found that 12-month-olds do not associate object features with agency or recipiency, 14-month-olds associate any object features with these causal roles, and 16-month-olds associate only those features with causal roles that match those in the real world. (Although older infants

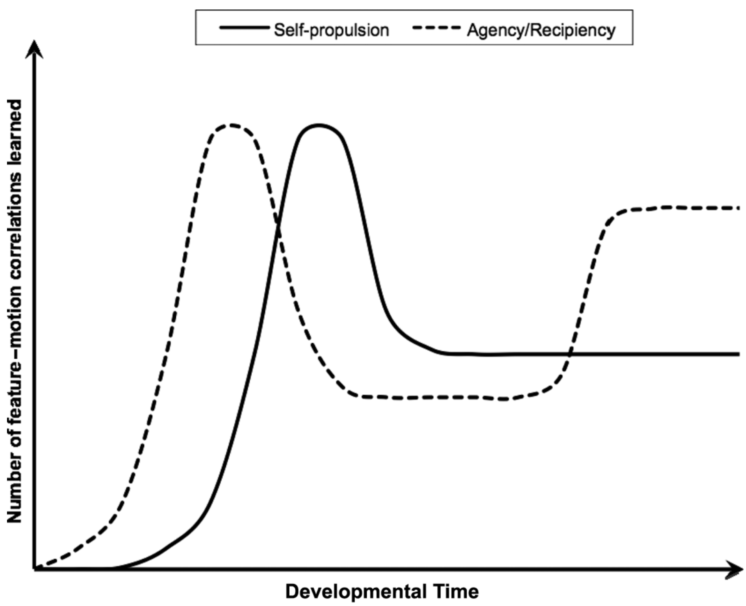

FIGURE 1 Example of N- and U-shaped curves found by Rakison (2005, 2006) with infants between 12 and 20 months of age. Infants initially learned no feature–motion correlations, then learned all feature–motion correlations (e.g., agents and recipients have moving features), and then learned only those feature–motion correlations that were consistent with the real world (e.g., agents have moving features). The final increase in the curve was predicted to occur later in development because adults are cognizant of the fact that agents and recipients can have moving features.

were not tested in this paradigm, it is evident that adults understand that recipients of an action can be animates and possess dynamic features.) Note that the nature of the correct or appropriate responses on the N-shaped curve changes with development. The 14-month-old infants' correct learning of the associations between object features and agency or recipiency was due to their indiscriminant learning of all available correlations. In contrast, the 16-month-olds' correct learning was due to their learning being constrained by prior experiences.

It is important to note that in many cases what is called a U- or N-shaped curve involves only an apparent regression (Goldin-Meadow, 2004; Marcovitch & Lewkowicz, 2004). For example, one of the earliest noted and famous U-shaped curves refers to the child's apparent deterioration from saying, for example, "broke" to "breaked." However, in this case, the child actually made cognitive advances that only appear, on the surface, as a regression; that is, the child discovered that "ed" tends to be a predominant past-tense word ending and overgeneralized it to irregular verbs. According to one view, this pattern is an epiphenomenon of humans' innate language faculty whereby memorized irregular forms cannot be recalled and instead the regular form is produced with the rule that suffixes "ed" to the stem (Marcus et al., 1992; Pinker, 1984). An alternative perspective, developed by Rumelhart and McClelland (1986), is that this pattern results from all-purpose associative learning mechanisms that link phonological features of the stem with phonological features of the past-tense form.

This example stresses an important aspect of our proposal; namely, the trend itself—regardless of whether it is an artifact or not—may tell us something about the mechanism that underlies developmental change. It is generally assumed that many, if not all, U- and N-shaped curves may involve a regression in one aspect of performance (e.g., learning fewer feature–motion correlations) and an overall advance in cognitive development (e.g., representing the feature–motion correlations in the world). Thus, the key point is that irrespective of whether these trends are an artifact of overall improvements in children's knowledge and abilities, they nonetheless are a marker of domain-general learning. This conclusion implies that the trend observed in children's acquisition of irregular verb endings may also result from such all-purpose learning mechanisms, as argued by Rumelhart and McClelland (1986).

N-shaped curves are not limited to cognitive development and also can be found in motor and social learning. For example, Adolph (1997) has shown that infants fail to transfer locomotion knowledge from crawling to walking. Although infants mastered which surfaces were safe and which were risky for crawling, this information had to be reacquired when infants first started walking. However, given that a discussion of all areas of development is beyond the scope of this article, we focus here on U- and N-shaped curves in perceptual and cognitive development.

Our claim about the mechanisms that underpin N-shaped and U-shaped trends stems largely from the fact that these trends have been observed—as we will demonstrate—in studies across a multitude of domains. These include behavioral studies on infants' learning of object properties, faces, language, and gesture, as well as Event-Related Potential (ERP) studies with infants and toddlers, and a number of Parallel Distributed Processing (PDP) models that are based on domain-general principles. We suggest, then, that the existence of the same non-monotonic developmental trend across many distinct domains implies that all-purpose mechanisms were responsible for learning for each of them. To be clear, we are not proposing that the operation of all domain-general mechanisms results in N- or U-shaped trends in development. Rather, we are suggesting the converse, that all N- or U-shaped curves are a result of domain-general mechanisms.

WHY ARE U- AND N-SHAPED TRENDS THE RESULT OF DOMAIN-GENERAL LEARNING?

There are four main reasons why domain-general learning—rather than domain-specific learning—would produce such trends. First, domain-general mechanisms become more powerful as information-processing abilities improve (e.g., memory, processing speed) and neurological maturation occurs (Rakison & Lupyan, 2008), which can explain the two increases in performance that are observed. That is, there is an improvement in learning and performance on a task as children are better able to process, encode, and recall information. An excellent example of such an improvement derives from habituation, or the decrease in attention over time to a stimulus as it is presented repeatedly. A large database of studies with infants attests to the fact that they habituate more quickly over developmental time as the ability to process information increases (see Hunter & Ames, 1988). It is true that such changes—that is, increases in performance because of information-processing advances—would have a similar effect on domain-specific learning. However, according to a number of theories, it is the "triggering" of modules or domain-specific processes by the appropriate input that causes jumps and advances in performance (e.g., Leslie, 1995; Mandler, 1992).

Second, and on a related note, U- and N-shaped curves are consistent with a number of domain-general, information-processing principles (Cohen, 1998; Cohen, Chaput, & Cashon, 2002). Perceptual and cognitive development, according to this view, is a constructive process whereby infants initially encode independent features and then later, following information-processing advances, encode relationships among those features. However, if infants' information-processing abilities are stretched or overwhelmed—when faced with too complex or too much information, for example—they fall back to processing independent features. Consistent with this view, Cashon and Cohen (2004) demonstrated that infants follow an N-shaped curve with respect to upright face processing and an inverted U-shaped curve for inverted faces. At 3 months, infants processed facial features independently for upright and inverted faces. By 4 months, infants integrated facial features for both, but by 6.25 months, infants dropped back down to processing individual features for both (perhaps because of attention to fine-grained detail or the addition of social information). Finally, by 7 months of age, infants began to integrate features of upright faces but not inverted faces. The authors attributed these results to changing levels of processing: Infants process faces initially at the level of individual features and proceed to higher levels of integration. However, when the information-processing system becomes overloaded, it forces infants back to a lower level of processing. To our knowledge, no domain-specific theories would predict such a pattern of performance over developmental time.

Third, domain-general mechanisms lead to the emergence of constraints on learning after experience with a structured input, which can explain the decline in performance that is seen after the initial improvement (see also Smith et al., 1996). That is, as infants form representations of the content and structure of the world, these representations limit and guide their future learning. Research by Werker and Tees (1983, 1984) provided an excellent illustration of this process. They found a decline in performance in infants' ability to discriminate phonemic contrasts such that younger infants discriminate both native and nonnative contrasts (e.g., two "d" sounds used in Hindi but that are heard as the same /d/ in English), but older infants—those around 10 to 12 months of age—discriminate only native phonemic contrasts. This emergence of constraints through experience is often considered a "narrowing effect," such that over developmental time infants lose the ability to discriminate or recognize stimuli within a domain (see e.g., Scott, Pascalis, & Nelson, 2007). This effect is entirely consistent with our proposal and may be the reason why a decline in infants' performance is often found. Note, however, that the presence of a narrowing effect does not necessarily imply that it is part of an N- or U-shaped curve. Adults, for example, rarely rediscover the ability to discriminate nonnative contrasts, and although they can do so with sufficient experience, this effect is rarely long lasting and does not generalize beyond the laboratory (e.g., Strange & Dittman, 1984). Thus, although the narrowing effect in some domains may be a part of the decline in the N- or U-shape curve, its presence does not necessarily imply that performance will improve later in developmental time.

What, then, is the mechanism by which some developmental declines enjoy a subsequent reemergence? This question can only be addressed by considering how constraints on learning emerge over developmental time. In our view, as infants and children experience the structure of the world, their learning is constrained by their representations of that structure. Or put another way, information structure emerges as domain-general mechanisms encode patterns of *coherent covariation* (Rogers & McClelland, 2004)—that is, joint presence or absence—among features of the input. As more information is encountered, learning of covariation patterns at different levels occurs and shifts the representational space. As a result, information that was previously consistent with the knowledge structure may become inconsistent and cause N- and U-shaped trends. We suggest that in all likelihood these constraints begin to loosen later in developmental time as children develop increasing executive control over the aspects of the array to which they attend and encode (Rakison & Lupyan, 2008). This, along with additional information-processing advances, causes the final improvement in performance that is observed in the U- or N-shaped curve.

Note that the development of learning constraints is essential to understanding why the same domain-general mechanisms can result in different developmental timelines for the emergence of U- and N-shaped curves across domains. Constraints emerge as a result of experience. However, the amount and complexity of input is variable across domains. Therefore, constraints emerge at different times as sufficient experience in different domains is accumulated, despite common mechanisms.

CAN DOMAIN-SPECIFIC MECHANISMS GIVE RISE TO THE SAME NON-MONOTONIC TRENDS?

In our view, there are at least four reasons why it is unlikely that domain-specific mechanisms would give rise to this pattern of development. First, once innate constraints and mechanisms are triggered, performance on tasks in a given knowledge domain should improve monotonically. To our knowledge, theorists who adopt a domain-specific approach have not generated the alternative prediction that performance or knowledge should decline following an initial improvement. Second, a number of proposed domain-specific mechanisms require little or no experience to operate at a highly functional level, and it is extremely unlikely that such mechanisms would show significant developmental decline following such an abrupt onset of mastery (e.g., Leslie, 1995; Spelke, 1994).

Third, the notion that learning constraints emerge within a specific domain as a result of the learning process is inconsistent with the idea that such constraints are built in at birth through core principles or domain-specific learning mechanisms as has been suggested by some theorists (e.g., Leslie, 1995; Mandler, 1992; Premack, 1990; Spelke, 1994). Those proponents of the domain-specific perspective who subscribe to this view of innate specifications would not predict that children are initially unconstrained in the information they will encode and then later become more limited in the information that they will learn. Instead, the domain-specific perspective implies that once a mechanism is operational it will cause infants to attend to, and interpret, certain events in specific ways (e.g., Leslie, 1995; Premack, 1990). However, it is important to point out that not all proponents of domain specificity view innateness of constraints as necessary.

Fourth, the view that non-monotonic trends could arise as a result of the interaction of multiple domain-specific constraints is unparsimonious because it suggests that many mechanisms, rather than one, give rise to the same learning trend. This argument also applies to the possibility that this trend emerges from an interaction between domain-specific and domain-general mechanisms such that a shift in, for example, attention and memory allocation by a general mechanism causes an increase or decline in behavior driven by the specialized mechanisms. Moreover, as we argued above, domain-specific mechanisms, even those that work in conjunction with each other, should give rise to monotonic, rather than curvilinear developmental trends.

At the same time, it is important to note that there are theorists—most notably Baillargeon (2001; Luo & Baillargeon, 2005)—who have proposed that infants possess innate primitive concepts that are enriched through experience. Although Baillargeon's (1995, 1999, 2001) claim is that specialized learning mechanisms enhance infants' knowledge based on experience, there is evidence from her laboratory of a "narrowing effect" in the domain of physical knowledge. For example, Luo and Baillargeon (2005) demonstrated that infants had a narrowing category of events that should result in occlusion. They found that 2.5-month-olds expect objects that move behind any screen to be occluded, even screens with a window, whereas 3-month-olds expected all objects that disappeared behind a screen with a continuous lower edge to be occluded (even if there was a window at the top of the screen). Luo and Baillargeon argued that infants progressively identified three variables important for occlusion—behind, continuous lower edge, and height of object—that narrow down the events that result in occlusion. It remains to be seen whether this effect is comparable to the U- and N-shaped curves we described earlier. One possibility is that the mechanisms by which infants show "incremental knowledge" are all purpose rather than, as Baillargeon (1999) proposed, specialized. Moreover, in our view, the "variables" that infants use to narrow occlusion events are equivalent to learning constraints such that they limit the information that infants are willing to encode.

Finally, it is also feasible that the final increase in performance in an N-shaped curve is the result of the emergence of domain-specific expertise from initially general processes. For example, it has been shown that bird experts categorize birds according to a different taxonomy than bird novices (Bailenson, Shum, Atran, Medin, & Coley, 2002). According to some theorists, such expertise is the result of a specific folk-biological system that allows humans to discriminate and categorize various taxonomies (e.g., Medin & Atran, 2004). Our claim, in contrast, is that domain-general mechanisms give rise to domain-specific expertise with sufficient experience and can eventually lead to the creation of domain-specific knowledge and strategies. This view is consistent with that offered to explain expertise in face recognition, and it has been suggested that a similar process operates across a range of domains for which an individual has sufficient exposure. For instance, adults with relevant experience can make exceptionally fine discriminations between dogs of the same subordinate category (Diamond & Carey, 1986) and can sex-type chickens with more than 99% accuracy (Gibson, 1969). In our view, such expert knowledge is not a result of some specific discrimination or categorization mechanisms, but rather a result of a domain-general mechanism operating over a large body of experience in a specific domain.

BIOLOGICAL PLAUSIBILITY

Our proposal can be critically evaluated by examining the biological plausibility of N-shaped curves across domains. Is it possible for brain systems to support non-monotonic changes in behavior? Current research suggests that N-shaped curves are compatible with brain maturation processes in infancy—in particular, synaptogenesis, myelination, and specialization. Cortical maturation is characterized by progressive and regressive patterns: Synaptic density increases from conception, peaking in early childhood, and is followed by synaptic pruning as children's brains become more like those of adults (Casey, Tottenham, Liston, & Durston, 2005). Synaptogenesis and pruning do not occur concurrently throughout the brain. Synaptic density peaks in visual and auditory areas around 3 months of age and is consistently higher than the density in the prefrontal cortex until 3.5 years of age (Huttenlocher & Dabholkar, 1997). Overall, synaptogenesis and pruning occur first in sensorimotor areas, followed by the temporal and parietal association cortex, and finally the prefrontal cortex (Casey et al., 2005).

Concurrent with the process of synaptogenesis, the brain also undergoes myelination of axons, which allows for more efficient signal transmission. In contrast to the inverted U-shaped curve of synapse formation, myelination is a monotonically increasing process (Casey et al., 2005). However, similar to synapse formation, myelination does not occur simultaneously throughout the brain. For example, the occipital region tends to myelinate before the frontal region (Martin et al., 1988).

In addition to synapse formation and myelination, the brain also undergoes shifts in specialization. For example, in infancy, face processing is initially handled by subcortical structures, followed by areas typically associated with language processing in adults, such as the superior temporal gyrus and the left-inferior frontal gyrus (Paterson, Heim, Friedman, Choudhury, & Benasich, 2006). ERP studies have also shown developmental changes in the processing of face information. Components of faces are processed in separate stages in infancy, which are marked by the N290 and P400 waveforms, which then come to be integrated into the adult N170 marker of face processing (Halit, de Haan, & Johnson, 2003). There is also an overall specialization shift from broadly recruiting sensory areas to recruiting more focused areas of the prefrontal cortex with respect to cognitive control processes related to working memory and inhibitory control (Casey et al., 2005).

Taken together, these findings emphasize the asynchronous nature of the maturation of different brain regions. One region of the brain may be undergoing synaptic pruning at the same time that another region is still in the process of generating synapses. In addition, different rates of myelination throughout the brain contribute to different processing efficiencies in different areas. The processes of synapse formation and myelination must also interact with the shifts in specialization that occur in the brain. In our view, these interactions may give rise to the non-monotonic developmental patterns observed in behavioral studies. Performance in behavioral experiments is underwritten by interactions of multiple areas of the brain, which may be undergoing synaptogenesis and myelination at different rates. As a result, this interaction between areas with changing synapse densities and degrees of myelination may lead to progressive and regressive behavioral outcomes. In addition, shifts in specialization such as those observed for face processing may also lead to regressions if the shift occurs to an area in a different stage of myelination or synapse formation. Although additional research is necessary that examines how different areas of the brain interact in infancy, we view this as a potential explanation for the biological plausibility of our proposal.

EMPIRICAL EVIDENCE IN SUPPORT OF OUR VIEW

We suggest that in conjunction, the four processes outlined earlier can account for many if not all U- and N-shaped curves observed in early development. In the following section, we outline evidence from a range of domains that support this view. In our view, it is important to demonstrate that these trends emerge with different methodologies, across different domains, and with a variety of age groups, because it suggests that they are not an artifact of any one approach to studying development. Unfortunately, in many cases, this research demonstrates only part of the N- or U-shaped curve because not all of the necessary age groups were tested. For example, developmental researchers often fail to include a younger age group that would fail completely on a task or older children who would succeed on many variations of the task. Nonetheless, the studies described here all show that the same basic trend—a decrease and increase in performance over developmental time—is evident across a wide range of domains of study.

Learning about Objects

Properties of objects. An important aspect of infant concept development involves learning about the properties of complex objects with multiple parts. Madole and Cohen (1995) examined how infants learn about one of these properties, namely, the correlation between what parts look like and what they do. They found that both 14- and 18-month-old infants learned the correlation between the appearance of a part and its function. However, only 14-month-olds learned the correlation between the appearance of one part and the function of a different part of the object. In other words, younger infants learned any relationship between parts and function, but older infants—who presumably were constrained by their real-world experience—learned only those correlations that were consistent with their previous experience. A similar pattern of results was found by Rakison (2005, 2006) for infants' learning about the features of agents, recipients, and self-propelled objects.

Properties of humans. We have already described work on infants' face perception that demonstrated a U- and N-shaped curve (Cashon & Cohen, 2004). However, infants show a similar effect when processing faces of a different race from their own, known as the *other-race effect*. Kelly et al. (2007), for example, found that 3-month-old Caucasian infants recognized Caucasian, African, Middle Eastern, and Chinese faces, 6-month-olds recognized only Chinese and Caucasian faces, and 9-month-olds recognized only Caucasian faces. In addition, there is evidence that newborns are unable to make these discriminations (Kelly et al., 2005) and that adults can recognize faces of all races, although their discrimination of other-race faces may not be at the level of same-race faces (Michel, Caldara, & Rossion, 2006). Thus, the N-shaped trend is present over developmental time in same- and other-race face processing. Kelly et al.'s (2007) interpretation of their findings was consistent with our earlier proposal: Infants were more likely to be exposed to faces of their own race, which increased their familiarity, preference, and ability to discriminate those faces. A similar pattern was also obtained from research on infants' ability to recognize human and monkey faces (Pascalis, de Haan, & Nelson, 2002) and infants' ability to discriminate point-light displays of walkers and runners (Booth, Pinto, & Bertenthal, 2002).

Language Learning

Speech perception. We have already outlined classic work by Werker and Tees (1983, 1984) on infants' ability to discriminate native and nonnative speech sounds. A comparable effect was also found by Stager and Werker (1997) for native phoneme discrimination. They showed that 8-month-old infants could distinguish similar-sounding novel words (i.e., bih and dih) in the context of an object but that 14-month-olds could not. When these words were presented without an object, both 8- and 14-month-olds could discriminate the speech sounds (cf., Rost & McMurray, 2009). This difference in performance was interpreted as resulting from the 14-month-olds (but not the 8-month-olds) approaching the first task as a labeling task but—as predicted by the information-processing approach—lacking the cognitive capacity to attend to fine differences between phonemes (cf., Thiessen, 2007).

In addition to discriminating words, infants must also segment individual words from whole utterances. Shi, Cutler, Werker, and Cruickshank (2006) demonstrated that over developmental time, infants narrowed the contexts under which they segmented words. Functor words such as "the" are good segmentation cues because they typically occur before a noun. Shi et al. (2006) found that 8-month-olds segmented words that occurred after the functor "the" and the similar-sounding nonword "kuh" and that 11-month-olds segmented words only after "the." The authors suggested that the 8-month-olds had a representation of the functor, but it was underspecified due to their lack of experience with words and included similar-sounding nonwords. As a result, the younger infants segmented words in a wider variety of contexts than 11-month-olds. Neither the 8- nor the 11-month-olds segmented after the functor "her"; however, older children can perform this segmentation, indicating an N-shaped curve in this domain.

Language and gesture. The same trend has also been found in studies that examined infants' acquisition of labels for objects. Namy, Campbell, and Tomasello (2004), for example, found that 18-month-olds and 4-year-olds will learn both arbitrary and iconic gestures for objects whereas 24-month-olds will learn only iconic gestures for objects. In a similar vein, Namy and Waxman (1998) found that 18-month-olds associate both novel words and novel gestures with categories but that 26-month-olds associate only novel words with categories, and Woodward and Hoyne (1999) demonstrated that when infants were presented with objects accompanied by novel sounds or words, 13-month-olds learned the sound–object and word–object associations. In contrast, 20-month-olds only associated words and objects.

Further Evidence

ERP research. ERP studies have been used to investigate a process of perceptual narrowing across domains whereby infants' ability to make discriminations that are not relevant in their environments declines with development (Scott et al., 2007). For example, infants can discriminate monkey faces at 6 months but not at 9 months of age (Pascalis et al., 2002). Two specific findings from ERP studies are relevant to our proposal regarding N-shaped curves as a marker of domain-general development. First, studies have shown that the brain comes to respond only to events consistent with prior experiences and that these responses become more focused. For example, Sheehan, Namy, and Mills (2007) demonstrated different ERP responses to word and gesture labels in 18- and 26-month-old infants. Eighteen-month-old infants showed an N400 component distributed throughout the scalp when words or gestures did not match their picture referents. This component was more narrowly distributed in the 26-month-olds and occurred only for word–picture mismatches. These ERP results both support and extend the Namy et al. (2004) findings discussed above.

Second, studies have shown that ERP evidence of discrimination can be found in infants who no longer show behavioral discrimination of stimuli not relevant in their environment. For example, 9-month-old infants show a greater P400 amplitude to familiar than unfamiliar monkey faces, despite failing to discriminate the two behaviorally (Scott, Shannon, & Nelson, 2006). This finding suggests that the behavioral regression may not be permanent at this stage. This hypothesis is supported by evidence showing that infants retain the behavioral ability to discriminate monkey faces through 9 months of age when they are given experience with monkey faces through storybooks that they read at home (Pascalis et al., 2005).

In our view, these findings on perceptual narrowing are consistent with our proposal. They show that infants' behaviors may exhibit a regression as a function of experience, whereby their response declines to information that is irrelevant to or inconsistent with the typical events seen in the environment. However, they also show that this may not be a full regression. Changing the distribution of events that infants experience by making previously irrelevant information more relevant or familiar can reverse the regression. This is consistent with the second peak of the N-shaped developmental pattern that we propose.

Computational modeling. There are number of reasons why the processes we have outlined to explain U- and N-shaped curves are highly compatible with PDP approaches to modeling development. First, the PDP approach is intrinsically domain general such that learning results from all-purpose mechanisms that were not specially designed for a particular domain. Second, PDP models exhibit properties that are consistent with the domain-general, information-processing principles outlined by Cohen (1998; Cohen et al., 2002). Third, constraints on learning emerge in PDP models as a result of the learning process itself. It is perhaps not surprising, then, that connectionist modeling approaches have been used to provide evidence for an associative learning basis for the emergence of U-shaped curves in development.

One example of such a model was generated by Rakison and Lupyan (2008) who successfully replicated the inverted U-shaped curves in infants' learning about agency (Rakison, 2005) and self-propulsion (Rakison, 2006) using a PDP framework. Rogers, Rakison, and McClelland (2004) also used a PDP approach to demonstrate the emergence of an N-shaped curve in the attribute of a particular feature (e.g., "has fur") to a category of objects (e.g., bats). As we discussed earlier, this pattern was hypothesized to be the result of the coherent covariation of features within categories. Notably, both of these simulations incorporated the idea that constraints on learning may arise due to the interaction between a fast-learning hippocampal system and a slow-learning neocortical system (see also McClelland, McNaughton, & O'Reilly, 1995). It is feasible that this interaction may be crucial to the emergence of U- and N-shaped curves, particularly those observed during the early period of development. This is because as a child has more experience over developmental time, novel stimuli are increasingly "filtered" through this experience and constrained by consistencies that were previously learned. Finally, Rumelhart and McClelland (1986) demonstrated that a connectionist model can account for the U-shaped curve in the overregularization of irregular English verbs by children. Specifically, it was shown that this developmental trend emerges as a result of the changing distribution of regular and irregular forms to which children are exposed.

CONCLUDING REMARKS

In a special issue of the *Journal of Cognition and Development*, a number of researchers—all of whom favor a domain-general approach to development—provided empirical evidence of U-shaped development (Cashon & Cohen, 2004; Gershkoff-Stowe & Thelen, 2004; Namy et al., 2004). In one of the subsequent commentaries, Marcus (2004) claimed that the multiplicity of factors that give rise to such trends within each domain means that "every U-shaped phenomenon must be studied independently" (p. 120). Although we agree that U- and N-shaped trends can and do result from a number of interacting concurrent developmental changes, we disagree wholeheartedly with the core of Marcus's statement. Indeed, in this article we have proposed just the opposite, namely that it is only when N-shaped and U-shaped developmental trends are considered together that it becomes apparent that they are indicative of domain-general learning. We outlined how such trends are generated by an improving information-processing system that is initially unconstrained in the information that it will encode, with constraints on learning emerging because of the learning process itself. A number of arguments were provided for why domain-specific mechanisms should not lead to the same kinds of developmental trends, and studies were described that exhibit the same trends across a range of domains. As we posited earlier, the existence of the same basic trend across so many domains strongly implies that the same mechanism underlies learning in all them. Our discussion has focused primarily on the developmental trends across the first few years of life. However, when we look at development more broadly across the lifespan, we can view it as an M-shaped rather than an N-shaped curve. For example, it has been shown that discrimination of phonemes such as /ba/ and /pa/ is worse in older adults as compared with younger adults (Strouse, Ashmead, Ohde, & Grantham, 1998).

A potential criticism of our hypothesis is that it is unfalsifiable. We believe, however, that it is entirely testable. For example, one method would be to establish that dedicated mechanisms underpin learning in a domain and that children's performance in that domain generates a U- or N-shaped trend. Clearly, this approach is predicated on the idea that it is possible empirically to show the existence of domain-specific mechanisms. An alternative approach is to demonstrate that domain-general learning does not necessarily give rise to U- and N-shaped curves. Although this method does not logically falsify our hypothesis, we believe that it is crucial to demonstrate that such trends emerge across a wide range of domains when infants and children acquire new information about those domains. The research by Werker and colleagues (Stager & Werker, 1997; Werker & Tees, 1983, 1984) and Namy and colleagues (Namy et al., 2004; Sheehan et al., 2007) provide excellent examples of these approaches.

One final important issue is why the N- and U-shaped trends are not observed more often. Does this imply that domain-general learning is limited to the examples we have provided here? We think not. In our view, many developmental scientists fail to adopt a truly developmental approach by testing participants across a wide range of ages. One reason for this is that it is often difficult to generate a homotypic metric to assess performance at different ages that would allow one to draw meaningful conclusions. Some U- and N-shaped trends may not be measurable or observable because the same methodology is not appropriate for all the age groups that need to be studied. A second, and more troubling, reason is that it is often assumed that once performance increases it will continue in this way. In other words, researchers assume that there is no need to show at what younger age children are unable to complete a task, and it is unnecessary to demonstrate that older children or adults can also succeed on it. Our hope is that an awareness of the implication of U- and N-shapes will not only engender developmental scientists to chart the full range of performance for infants and children over time but will also allow patterns in these data to be interpreted correctly from a theoretical standpoint.

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REFERENCES

Adolph, K. E. (1997). Learning in the development of infant locomotion. *Monographs of the Society for Research in Child Development*, *62*(3), 1–162.

Bailenson, J. N., Shum, M. S., Atran, S., Medin, D. L., & Coley, J. D. (2002). A bird's eye view: Biological categorization and reasoning within and across cultures. *Cognition*, *2002*, 1–53.

Baillargeon, R. (1995). Physical reasoning in infancy. In M. S. Gazzaniga (Ed.), *The cognitive neurosciences* (pp. 181–204). Cambridge, MA: MIT Press.

Baillargeon, R. (1999). Young infants' expectations about hidden objects: A reply to three challenges (article with peer commentaries and response). *Developmental Science*, *2*, 115–163.
Baillargeon, R. (2001). Infants' physical knowledge: Of acquired expectations and core principles. In E. Dupoux (Ed.), *Language, brain, and cognitive development: Essays in honor of Jacques Mehler* (pp. 341–361). Cambridge, MA: MIT Press.
Booth, A. E., Pinto, J., & Bertenthal, B. I. (2002). Perception of the symmetrical patterning of human gait by infants. *Developmental Psychology*, *38*, 554–563.
Casey, B. J., Tottenham, N., Liston, C., & Durston, S. (2005). Imaging the developing brain: What have we learned about cognitive development? *TRENDS in Cognitive Sciences*, *9*, 104–110.
Cashon, C. H., & Cohen, L. B. (2004). Beyond U-shaped development in infants' processing of faces: An information-processing account. *Journal of Cognition and Development*, *5*, 59–80.
Cohen, L. B. (1998). An information-processing approach to infant perception and cognition. In F. Simion & G. Butterworth (Eds.), *The development of sensory, motor, and cognitive capacities in early infancy* (pp. 277–300). East Sussex, UK: Psychology Press.
Cohen, L. B., Chaput, H. H., & Cashon, C. H. (2002). A constructivist model of infant cognitive development. *Cognitive Development*, *17*, 1323–1343.
Diamond, R., & Carey, S. (1986). Why faces are and are not special: An effect of expertise. *Journal of Experimental Psychology: General*, *115*, 107–117.
Gelman, R. (1990). First principles organize attention to and learning about relevant data: Number and the animate–inanimate distinction as examples. *Cognitive Science*, *14*, 79–106.
Gershkoff-Stowe, L., & Thelen, E. (2004). U-shaped changes in behavior: A dynamic systems perspective. *Journal of Cognition and Development*, *1*(5), 11–36.
Gibson, E. J. (1969). *Principles of perceptual learning and adaptation.* New York, NY: Appleton-Century-Crofts.
Goldin-Meadow, S. (2004). U-shaped changes are in the eye of the beholder. *Journal of Cognition and Development*, *5*, 109–111.
Haith, M. M. (1998). Who put the cog in infant cognition: Is rich interpretation too costly? *Infant Behavior and Development*, *21*, 167–179.
Halit, H., de Haan, M., & Johnson, M. H. (2003). Cortical specialization for face processing: Face-sensitive event-related potential components in 3- and 12-month-old infants. *NeuroImage*, *19*, 1180–1193.
Hunter, M. A., & Ames, E. W. (1988). A multifactor model of infant preferences for novel and familiar stimuli. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 5, pp. 69–95). Norwood, NJ: Ablex.
Huttenlocher, P. R., & Dabholkar, A. S. (1997). Regional differences in synaptogenesis in human cerebral cortex. *The Journal of Comparative Neurology*, *387*, 167–178.
Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Ge, L., & Pascalis, O. (2007). The other-race effect develops in infancy: Evidence of perceptual narrowing. *Psychological Science*, *18*, 1084–1089.
Kelly, D. J., Quinn, P. C., Slater, A. M., Lee, K., Gibson, A., Smith, M., ... Pascalis, O. (2005). Three-month-olds, but not newborns, prefer own-race faces. *Developmental Science*, *8*, 31–36.
Leslie, A. (1995). A theory of agency. In D. Sperber, D. Premack, & A. J. Premack (Eds.), *Causal cognition* (pp. 121–141). Oxford, NY: Clarendon.
Luo, Y., & Baillargeon, R. (2005). Can a self-propelled box have a goal? Psychological reasoning in 5-month-old infants. *Psychological Science*, *16*, 601–608.
Madole, K. L., & Cohen, L. B. (1995). The role of object parts in infants' attention to form-function correlations. *Developmental Psychology*, *31*, 637–648.
Madole, K. L., & Oakes, L. M. (1999). Making sense of infant categorization: Stable processes and changing representations. *Developmental Review*, *19*, 263–296.

Mandler, J. M. (1992). How to build a baby: II. Conceptual primitives. *Psychological Review*, *99*, 587–604.

Marcovitch, S., & Lewkowicz, D. J. (2004). U-shaped functions: Artifact or hallmark of development? *Journal of Cognition and Development*, *5*, 113–118.

Marcus, G. F. (2004). What's in a U? The shapes of cognitive development. *Journal of Cognition and Development*, *5*, 119–122.

Marcus, G. F., Pinker, S., Ullman, M., Hollander, M., Rosen, T. J., & Xu, F. (1992). Overregularization in language acquisition. *Monographs of the Society for Research in Child Development*, *57*(4, Serial No. 228).

Martin, E., Kikinis, R., Zuerrer, M., Boesch, C., Briner, J., Kewitz, G., & Kaelin, P. (1988). Developmental stages of human brain: An MR study. *Journal of Computer-Assisted Tomography*, *12*, 917–922.

McClelland, J. L., McNaughton, B. L., & O'Reilly, R. C. (1995). Why there are complementary learning systems in the hippocampus and neocortex: Insights from the successes and failures of connectionist models of learning and memory. *Psychological Review*, *102*, 419–457.

Medin, D., & Atran, S. (2004). The native mind: Biological categorization and reasoning in development and across cultures. *Psychological Review*, *111*, 960–983.

Michel, C., Caldara, R., & Rossion, B. (2006). Same-race faces are perceived more holistically than other-race faces. *Visual Cognition*, *14*, 55–73.

Namy, L. L., Campbell, A. L., & Tomasello, M. (2004). Developmental change in the role of iconicity in symbol learning. *Journal of Cognition and Development*, *5*, 37–57.

Pascalis, O., de Haan, M., & Nelson, C. A. (2002). Is face processing species specific during the first year of life? *Science*, *296*, 1321–1323.

Pascalis, O., Scott, L. S., Kelly, D. J., Shannon, R. W., Nicholson, E., Coleman, M., & Nelson, C. A. (2005). Plasticity of face processing in infancy. *Proceedings of the National Academy of Sciences*, *102*, 5297–5300.

Paterson, S. J., Heim, S., Friedman, J. T., Choudhury, N., & Benasich, A. A. (2006). Development of structure and function in the infant brain: Implications for cognition, language, and social behavior. *Neuroscience and Biobehavioral Reviews*, *30*, 1087–1105.

Pinker, S. (1984). *Language learnability and language development*. Cambridge, MA: Harvard University Press.

Premack, D. (1990). The infants' theory of self-propelled objects. *Cognition*, *36*, 1–16.

Quinn, P. C., & Eimas, P. D. (1997). A reexamination of the perceptual-to-conceptual shift in mental representations. *Review of General Psychology*, *1*, 171–187.

Rakison, D. H. (2005). A secret agent? How infants learn about the identity of objects in a causal scene. *Journal of Experimental Child Psychology*, *91*, 271–296.

Rakison, D. H. (2006). Make the first move: How infants learn the identity of self-propelled objects. *Developmental Psychology*, *42*, 900–912.

Rakison, D. H., & Lupyan, G. (2008). Developing object concepts in infancy: An associative learning perspective. *Monographs of SRCD*, *73*, 1–130.

Rogers, T. T., & McClelland, J. L. (2004). *Semantic cognition: A parallel distributed processing approach*. Cambridge, MA: MIT Press.

Rogers, T. T., Rakison, D. H., & McClelland, J. L. (2004). U-shaped curves in development: A PDP approach. *Journal of Cognition and Development*, *5*, 137–145.

Rost, G. C., & McMurray, B. (2009). Speaker variability augments phonological processing in early word learning. *Developmental Science*, *12*, 339–349.

Rumelhart, D. E., & McClelland, J. L. (1986). On learning the past tenses of English verbs. In J. L. McClelland, D. E. Rumelhart, & the PDP Research Group. *Parallel distributed processing: Explorations in the microstructure of cognition* (Vol. 2, pp. 216–271). Cambridge, MA: MIT Press.

Scott, L. S., Pascalis, O., & Nelson, C. A. (2007). A domain-general theory of the development of perceptual discrimination. *Current Directions in Psychological Science*, *16*, 197–201.
Scott, L. S., Shannon, R. W., & Nelson, C. A. (2006). Neural correlates of human and monkey face processing by 9-month-old infants. *Infancy*, *10*, 171–186.
Sheehan, E. A., Namy, L. L., & Mills, D. L. (2007). Developmental changes in neural activity to familiar words and gestures. *Brain and Language*, *101*, 246–259.
Shi, R., Cutler, A., Werker, J., & Cruickshank, M. (2006). Frequency and form as determinants of functor sensitivity in English-acquiring infants. *Journal of the Acoustical Society of America*, *119*, EL61–EL67.
Smith, L., Jones, S., & Landau, B. (1996). Naming in young children: A dumb attentional mechanism? *Cognition*, *60*, 143–171.
Spelke, E. S. (1994). Initial knowledge: Six suggestions. *Cognition*, *50*, 431–445.
Spelke, E. S., Breinlinger, K., Macomber, J., & Jacobson, K. (1992). Origins of knowledge. *Psychological Review*, *99*, 605–632.
Stager, C. L., & Werker, J. F. (1997). Infants listen for more phonetic detail in speech perception than in word-learning tasks. *Nature*, *388*, 381–382.
Strange, W., & Dittman, S. (1984). Effects of discrimination training on the perception of /r–l/ by Japanese adults learning English. *Perception & Psychophysics*, *36*, 131–145.
Strouse, A., Ashmead, D. H., Ohde, R. N., & Grantham, D. W. (1998). Temporal processing in the aging auditory system. *Journal of the Acoustical Society of America*, *104*, 2385–2399.
Thiessen, E. D. (2007). The effect of distributional information on children's use of phonemic contrasts. *Journal of Memory and Language*, *56*, 16–34.
Werker, J. F., & Tees, R. C. (1983). Developmental changes across childhood in the perception of nonnative speech sounds. *Canadian Journal of Psychology*, *37*, 278–286.
Werker, J. F., & Tees, R. C. (1984). Cross-language speech perception: Evidence for perceptual reorganization during the first year of life. *Infant Behavior and Development*, *7*, 49–63.
Woodward, A. L., & Hoyne, K. L. (1999). Infants' learning about words and sounds in relation to objects. *Child Development*, *70*, 65–77.
Wynn, K. (1992). Addition and subtraction by human infants. *Nature*, *358*, 749–750.
Xu, F., & Garcia, V. (2008). Intuitive statistics by 8-month-old infants. *Proceedings of the National Academy of Sciences of the United States of America*, *105*, 5012–5015.