The Official Journal of the International Society on Infant Studies
Infancy

Infancy, **16**(1), 45–51, 2011

ISSN: 1525-0008 print / 1532-7078 online
DOI: 10.1111/j.1532-7078.2010.00054.x

WILEY-BLACKWELL

Early Perceptual Learning

Robert L. Goldstone
Department of Psychological and Brain Sciences
Indiana University

Ji Y. Son
Department of Psychology
California State University

Lisa Byrge
Department of Psychological and Brain Sciences
Indiana University

Bhatt and Quinn (2011) present a compelling case that human learning is *early* in two very different, but interacting, senses. Learning is *developmentally* early in that even infants show strikingly robust adaptation to the structures present in their world. Learning is also early in an information processing sense because infants' adapt their *perceptual* encodings and organizations at an early stage of neural processing. Both senses of ‘‘early'' speak to the importance of learning because they imply that learners are adapting their representations of their environment in a way that affects all ‘‘down-stream'' processing. Developmentally speaking, the learning that an infant enacts serves as the groundwork for all subsequent learning. In terms of information processing, adapting early-stage sensory and perceptual processes in turn affects all subsequent cognitive processes. There is evidence from neuroscience that interactions with an environment do cause early changes to primary

---

Correspondence should be sent to Robert L. Goldstone, Department of Psychological and Brain Sciences, Indiana University, 1101 E. 10th St., Bloomington, IN 47405. E-mail: rgoldsto@indiana.edu

sensory cortices (Goldstone, 1998; Vogels, 2010). One might generally suppose that it is advisable to be conservative in making such environment-driven cortical changes, given the ripples of influence caused by early learning in both senses. Manipulating grounding representations is a risky proposition. However, the evidence indicates that systems that need to respond effectively to their environment need to engage in both kinds of learning.

This very fact is worth dwelling upon. One might have thought that developmentally early perceptual learning would occur rarely because evolution should have already tuned our perceptual systems to be sensitive to the most important elements of the world in which we live (Olshausen & Field, 1996). Having an adaptive perceptual system is advantageous when the world is variable. However, at least at a first pass, is not the world fairly stable? We are all exposed to the same wavelengths of light thanks to the sun's spectral class. The gravitational constant is, here on earth, constant. Nonetheless, people do face different environments. To a large extent, a person's environment consists of animals, people, and things made by people. All of these things show local and regional variation, due to evolution and human design. If we need to be able to identify a particular plant, animal, person, or artifact, then this skill needs to be learnable. Furthermore, if we want the skill to be efficient, then it should become perceptual rather than strategic or reflective.

The field of biology is being transformed by an appreciation that two time courses of organismic change, evolutionary and developmental, interact with each other in important ways (Carroll, 2005). This Evo-Devo movement has discovered that a small set of regulatory genes shared by many different life forms have a large influence on the eventual form and function of organisms by modulating their development. It is tempting to include a third time course, that of processing of individual environmental inputs, to create an Evo-Devo-Info triumvirate of interacting and adaptive processes. Bhatt and Quinn (2011) provide some early details on what some of these interactions look like. One example of such an interaction is that evolutionary-scale learning can drive learning across the lifetime, which, in turn, drives adaptation of the information processing of individual events. Bhatt and Quinn describe Spelke's (1990) evidence that infants appear predisposed to treat parts of a display that move together as belonging to the same object. Once spatially separated parts of a display are joined together in the same object because of their common motion, the infant can learn about other systematic object properties, such as edges, smoothly varying contours, and uniform coloration. These secondary properties, once detected, undergo a learning process whereby they become processed by relatively early, in the sense of information processing stages, neural areas (Fahle & Poggio, 2002). In this manner, perceptual constraints that have been acquired on an evolutionary time scale lead to constraints that are acquired over an organism's lifetime, which constrain how individual events are processed. By this view, evolved perceptual processes are not opposed to learning processes. There is no "innate VERSUS learned" territory conflict. We have evolved so that experience with a richly and diversely structured world allows us to devise many of the constraints that we subsequently use to efficiently learn more from our world (Goldstone & Landy, 2010).

UNITIZATION, SELECTION, AND DIFFERENTIATION

Bhatt and Quinn (2011) describe five categories of learning experiences that lead infants to create new perceptual organizations. They propose two mechanisms of perceptual learning that underpin these five categories. The first is selective attention—learning to attend to relevant information and disregard irrelevant information. The second is unitization—learning to combine together elements to create larger, more complex configurations that come to be processed as a single entity. These two mechanisms are in some ways converses of each other. The first picks out and differentially weights elements from a larger whole. The second fuses elements together to create a whole. However, as Bhatt and Quinn observe, these two mechanisms are flip sides of the same coin—they create perceptual units of organization that effectively capture presented structure. When there is an element that occurs across several varying contexts and it is differentially diagnostic for an important task, then the element tends to be selectively attended (Needham & Baillargeon, 1998; Quinn & Bhatt, 2005b). When an element tends to co-occur with other elements, and together they are diagnostic, then the elements are joined together into a single unit. Many environments require both selective attention to parts and unitization, such as when infants learn to break a sound stream into separate speech units at the same time that they learn to group together the sounds from a single unit (Saffran, Aslin, & Newport, 1996). Sound elements are inferred to come from a single unit if there are high conditional probabilities between the elements, and to come from different units if the conditional probabilities are low.

To these complementary mechanisms of perceptual learning, we propose adding a third mechanism: attribute differentiation. To understand the importance of this third mechanism, it helps to reflect on the requirements of selective attention. Selective attention critically depends on perceptual attributes that have already been psychologically isolated. That is, it is only possible for an observer to attend to the brightness of a shape and ignore its size if the attribute of brightness has been isolated and separated from size. One standard conception for how attributes are isolated is for there to be a neurologically distinct brain region or perceptual channel responsible for the processing of the attribute. There is developmental evidence that attributes that are easily isolated by adults, such as the brightness and size of a square, are treated as fused together for 4-year-old children (Kemler & Smith, 1978; Smith & Kemler, 1978). It is relatively difficult for children to decide whether two objects are identical on a particular attribute, but relatively easy for them to decide whether they are similar across many attributes (Smith, 1989). For example, children seem to be distracted by shape differences when they are instructed to make comparisons based on color. Adjectives that refer to single attributes are learned by children relatively slowly compared to nouns (Smith, Gasser, & Sandhofer, 1997).

In some of the cases described by Bhatt and Quinn (2011), it is difficult to know whether attribute differentiation or selective attention is involved. In particular, when a child learns to respond to particular aspect of a complex object (Quinn & Bhatt, 2005a; Quinn & Schyns, 2003; Quinn, Schyns, & Goldstone, 2006), it could be that they are learning to selectively attend to already-isolated parts based on their form and/or location, or it could be that they are learning to isolate the part as a separate attribute of the object. Although the current state of the evidence may not be able to choose between these alternatives, we nonetheless believe that they are theoretically distinct and empirically distinguishable. For example, imagine two attributes, such as the brightness and saturation of a color, that are originally psychologically fused together into a perception of color (Garner, 1976). Repeatedly alternating training where saturation is task-relevant with training where brightness is task-relevant may succeed in isolating the two attributes, so that either of the attributes can be selectively attended while ignoring the other (Goldstone & Steyvers, 2001). Attribute differentiation does not reduce to selective attention because prior to this training, it might have been impossible for a person to selectively attend to either of these attributes while ignoring the other. After this training, there is a longer-term ability of the person to switch their attention to either of the two attributes. A task where only brightness is relevant might cause only brightness to be selectively attended, with saturation ignored, but saturation remains differentiated, as it can be rapidly selected by attentional processes if necessary.

If selective attention to an attribute can be understood as learning to weight that attribute heavily for a judgment, then attribute differentiation can be understood as learning to learn how to weight an attribute.

Even the possibility of genuine attribute differentiation might be denied. One might suppose that if two attributes are fused together at some point in perceptual processing, then they can never be split apart later. Once water has been mixed with wine, they cannot be unmixed. Fortunately, there are computational models that explain how attribute differentiation mechanisms might operate. Competitive learning neural networks differentiate inputs into categories by specializing detectors to respond to classes of inputs. Random detectors that are slightly more similar to an input than other detectors will learn to adapt themselves toward the input and will inhibit other detectors from doing so (Rumelhart & Zipser, 1985). A model that extended this mechanism to sorting object parts into detectors, when presented with an original set of training objects, was able to discover part-based building blocks that could be recombined to recreate the original training objects (Goldstone, 2003). Other learning systems show similar functional behavior by using Expectation Maxmization (Ghahramani, 1995) or Bayesian (Austerweil & Griffiths, 2009) methods. In short, recent advances in machine learning provide existence proofs of mechanisms for dimension differentiation. Water and wine can be separately extracted if one has not only a single mixed sample, but several samples with different proportions of water and wine.

Although there are working computational models and at least suggestive evidence that people can come to be able to differentiate originally fused attributes (Hockema, Blair, & Goldstone, 2005), we concur with Bhatt and Quinn's (2011) decision to stress selective attention and unitization. The evidence for attribute differentiation is controversial (Op de Beeck, Wagemans, & Vogels, 2003) and not as plentiful as the evidence for the other two mechanisms. However, our reason to discuss it here is because it seems like a fruitful avenue for future developmental research. There is reason to believe that attribute differentiation may play a particularly important role for infants. Namely, infants are in the business of creating the perceptual building blocks that will serve them a lifetime. Whereas selective attention can increase or decrease the importance given to existing building blocks, only attribute differentiation can create the building blocks in the first place. Whereas adults may be biased to interpret their world in terms of perceptual representations that they have already built, infants may be relatively predisposed to create new dimension and part representations. If so, this would be an interesting partial[1] exception to Bhatt and Quinn's expectation that perceptual learning is qualitatively similar across ages. Future work may reveal that infants, when exposed to a world of objects composed out of underlying parts or dimensions, are more likely to discover these elements than are adults, if general learning efficiency is controlled.

---

[1] The exception would only be partial because Bhatt and Quinn are mostly concerned with age differences within infancy, and because we are only arguing for the relative intransigence, not impossibility, of dimension differentiation in adults.

ACKNOWLEDGMENTS

The authors wish to express thanks to Linda Smith for helpful suggestions on this work. This work was funded by National Science Foundation REESE grant 0910218. More information about the laboratory can be found at http://cognitrn.psych.indiana.edu.

REFERENCES

Austerweil, J., & Griffiths, T. L. (2009). Analyzing human feature learning as nonparametric Bayesian inference. *Advances in Neural Information Processing Systems*, *21*, 386–492.

Bhatt, R. S., & Quinn, P. C. (2011). How does learning impact development in infancy? The case of perceptual organization. *Infancy*, *16*, 2–38.

Carroll, S. B. (2005). *Endless forms most beautiful: The new science of Evo Devo and the making of the animal kingdom*. New York: Norton.

Fahle, M., & Poggio, T. (2002). *Perceptual learning*. Cambridge, MA: MIT Press.

Garner, W. R. (1976). Interaction of stimulus dimensions in concept and choice processes. *Cognitive Psychology*, *8*, 98–123.

Ghahramani, Z. (1995). Factorial learning and the EM algorithm. In G. Tesauro, D. S. Touretzky, & T. K. Leen (Eds.), *Advances in Neural Information Processing Systems 7* (pp. 617–624). Cambridge, MA: MIT Press.

Goldstone, R. L. (1998). Perceptual learning. *Annual Review of Psychology*, *49*, 585–612.

Goldstone, R. L. (2003). Learning to perceive while perceiving to learn. In R. Kimchi, M. Behrmann, & C. Olson (Eds.), *Perceptual organization in vision: Behavioral and neural perspectives* (pp. 233–278). Mahwah, NJ: Lawrence Erlbaum Associates.

Goldstone, R. L., & Landy, D. H. (2010). Domain-creating constraints. *Cognitive Science*, *34*, 1357–1377.

Goldstone, R. L, & Steyvers, M. (2001). The sensitization and differentiation of dimensions during category learning. *Journal of Experimental Psychology: General*, *130*, 116–139.

Hockema, S. A., Blair, M. R., & Goldstone, R. L. (2005). Differentiation for novel dimensions. *Proceedings of the twenty-seventh annual conference of the cognitive science society* (pp. 953–958). Hillsdale, NJ: Lawrence Erlbaum Associates.

Kemler, D. G., & Smith, L. B. (1978). Is there a developmental trend from integrality to separability in perception? *Journal of Experimental Child Psychology*, *26*, 498–507.

Needham, A., & Baillargeon, R. (1998). Effects of prior experience on 4.5-month-old infants' object segregation. *Infant Behavior and Development*, *21*, 1–24.

Olshausen, B. A., & Field, D. J. (1996). Emergence of simple-cell receptive field properties by learning a sparse code for natural images. *Nature*, *381*, 607–609.

Op de Beeck, H., Wagemans, J., & Vogels, R. (2003). The effect of category learning on the representation of shape: Dimensions can be biased but not differentiated. *Journal of Experimental Psychology: General*, *132*, 491–511.

Quinn, P. C., & Bhatt, R. S. (2005a). Good continuation affects discrimination of visual pattern information in young infants. *Perception & Psychophysics*, *67*, 1171–1176.

Quinn, P. C., & Bhatt, R. S. (2005b). Learning perceptual organization in infancy. *Psychological Science*, *16*, 515–519.

Quinn, P. C., & Schyns, P. G. (2003). What goes up may come down: Perceptual process and knowledge access in the organization of complex visual patterns by young infants. *Cognitive Science*, *27*, 923–935.

Quinn, P. C., Schyns, P. G., & Goldstone, R. L. (2006). The interplay between perceptual organization and categorization in the representation of complex visual patterns by young infants. *Journal of Experimental Child Psychology*, *95*, 117–127.

Rumelhart, D. E., & Zipser, D. (1985). Feature discovery by competitive learning. *Cognitive Science*, *9*, 75–112.

Saffran, J. R., Aslin, R. N., & Newport, E. L. (1996). Statistical learning by 8-month-old infants. *Science*, *274*, 1926–1928.

Smith, L. B. (1989). From global similarity to kinds of similarity: The construction of dimensions in development. In S. Vosniadou & A. Ortony (Eds.), *Similarity and analogical reasoning* (pp. 146–178). Cambridge, UK: Cambridge University Press.

Smith, L. B., Gasser, M., & Sandhofer, C. (1997). Learning to talk about the properties of objects: A network model of the development of dimensions. In R. L. Goldstone, P. G. Schyns, & D. L. Medin (Eds.), *The psychology of learning and motivation, Vol. 36* (pp. 219–255). San Diego, CA: Academic Press.

Smith, L. B., & Kemler, D. G. (1978). Levels of experienced dimensionality in children and adults. *Cognitive Psychology*, *10*, 502–532.

Spelke, E. S. (1990). Principles of object perception. *Cognitive Science*, *14*, 29–56.

Vogels, R. (2010). Mechanisms of visual perceptual learning in macaque visual cortex. *Topics in Cognitive Science*, *2*, 239–250.