

Infants' Detection of Contingency: A Cognitive-Neuroscience Perspective

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Advances in developmental cognitive neuroscience have generated important and interesting data that are relevant to infants' perception of contingencies. The concepts of "binding" (i.e., the binding of stimulus properties across space, and binding of events across time) are discussed within the context of the cognitive neuroscience approach to learning. Issues relevant to infant contingency perception are discussed. Previously published data on infant contingency perception and discrimination learning from the author's laboratory are reinterpreted in terms of these binding concepts, and the development of the neural substrates that presumably underlie the perception of stimulus attributes and temporal redundancy.

The analysis of infants' detection and perception of contingency has a long and rich history. Seminal research in infant learning by Lipsitt (e.g., Lipsitt & Kaye, 1964) and Siqueland (1968) addressed the significance of the basic conditioning paradigms to developmental psychology. Millar (1972; Millar & Schaffer, 1972) conducted interesting work on the parameters of reinforcement. In particular, Watson (1967, 1972) sought to show how the infant's perception of contingency could be applied to both cognitive and social domains. Finally, contemporary researchers such as those represented here at this workshop have continued to carry this banner. In particular, Rochat (e.g., Rochat & Morgan, 1995; Rochat, Morgan, & Carpenter, 1997) has done careful and interesting work on the infant's perception of contingencies in the visuo-spatial realm.

My purpose here is to try and bring recent developments in the field of cognitive neuroscience and developmental cognitive neuroscience to bear on the topic of infant contingency perception. The blueprint for doing this is to first put forth some ideas about the cognitive neuroscience of contingency and of attention. The latter topic will emphasize recent advances in our understanding of attentional development during the first year of postnatal life. Then, some studies of infant contingency processing conducted some time ago in my laboratory will be presented, and reinterpreted in light of these recent advances. The paper concludes with the recommendation that investigation of early contingencies in any domain will greatly profit from a consideration of the development of CNS mechanisms underlying cognition and learning.

Binding and Learning

Psychologists have struggled with definitions of the concept of learning since the inception of the discipline. From a cognitive-neuroscience perspective, learning may be characterized simply as the detection and retention of correlated events (see, e.g., Gluck & Granger, 1993). It is clear from recent work in the cognitive neurosciences that the brain "strips down" and sorts input in modular ways. There are different sensory systems, each with its own subcortical pathways and cortical target loci. Even within sensory systems, it appears that events or stimuli are "stripped down" and sorted into different dimensions. It seems likely that understanding how the brain "binds" these properties, elements, or events is quite relevant to a consideration of contingency learning. In keeping with a connectionist and cognitive-neuroscience perspective, I would posit quite simply that the events or event properties are bound together (i.e., are aggregated to correlated percepts) through their temporal and spatial contiguity.

Spatial Binding. For example, there are two primary pathways for attention in the human brain (e.g., Webster & Ungerleider, 1998). A posterior pathway (which projects ultimately to parietal cortex) appears to direct attention to rather broad spatial loci (i.e., "where"), while an anterior pathway (which projects to temporal cortices) mediates the processing of particular visual features or elements (i.e., "what").

Compound visual stimuli appear to be stripped down to more elemental properties (e.g., form, color, texture, size; Robertson, 1998) and appear to be extracted by the anterior pathway (Corbetta, Shulman, Miezin, & Petersen, 1995). These elements, however, are probably bound by a common spatial code provided by the posterior pathway (Treisman & Gelade, 1980). In support of this notion, individuals with bilateral parietal

damage can identify object properties in isolation, but are impaired in their ability to search for compounds (e.g., Friedman-Hill, Robertson, & Treisman, 1995).

Temporal Binding. The binding of stimulus properties may be accomplished by virtue of spatial codes that are shared among such properties. However, the correlation among complex events is likely processed on the basis of shared time codes. Indeed, a considerable literature exists on the phenomenon of temporal binding (e.g., Engel, Koenig, Kreiter, & Schillen, 1992). Here, although input generated by contingent or co-occurring events may be directed to different brain systems, the events themselves are perceived as correlated by synchronized, coordinated, or parallel patterns of neural firing from these distributed areas (Engel, Fries, Koenig, Brecht, & Singer, 1999; Newman & Grace, 1999; see also Buonomano & Merzenich, 1995). Steinmetz et al. (2000) have recently shown that such patterns of synchronized neural firing are greatly enhanced when organisms turn or switch their attention to the modality being stimulated.

Indeed, the study of temporal information processing in the CNS has burgeoned in the last half of the 1990s (e.g., Buonomano & Merzenich, 1997; Tallal, Galaburda, Llinas, & von Euler, 1993). Merzenich and his colleagues (Jenkins, Merzenich, & Recanzone, 1990) have reported a particularly striking set of findings which show that synchronization of fine motor movements cause the merging of functional somesthetic maps of digits in the motor cortex. That is, if the movement of multiple digits are highly correlated (i.e., if the digits are made to move simultaneously in a chronic preparation), the cortical maps for those digits tend to fuse. Thus, noncontingent input maintains the separate identity of digits in the cortex, and contingent input tends to have the brain treat the digits as identical. (This latter situation has some interesting pathological implications for repetitive strain injuries; see Byl, Merzenich, & Jenkins, 1996). It is a leap (but, in my estimation, not a particularly long or unreasonable one) to extrapolate this general principle to the perception of the correlation of events (see, e.g., Watson, 1997).

Summary. Great strides have been made in the area of cognitive neuroscience over the past decade, and although it has not been generally recognized as such, much of this progress may be relevant to investigators interested in contingency analysis. I have briefly discussed

some very simple means by which the CNS may bind parallel but disparate sensory inputs into meaningful percepts. I raise the possibility that these fundamental processes may be the neural basis for contingency perception in humans across the lifespan.

My next task is to show how considerations from recent advances in developmental cognitive neuroscience may be brought to bear on some data pertaining to infant contingency processing that we had collected some time ago.

Stimulus and Positional Cues in Infant Learning: A Reinterpretation

In the early 1990s, our laboratory carried out a series of studies on infant discrimination learning in which we were able to analyze some of the bases on which 3-, 6- and 9-month-old infants perceived contingencies. This work was then extended by Jeff Coldren in critical tests of long-standing hypotheses about the development of attention to the perceptual features of visual stimuli (dimensions and attributes) in infants of various ages (Coldren, 1997; Coldren & Colombo, 1994). I mention this line of research in particular, because the connection between infant learning and infant attention is a strong and necessary one (cf. Hayes, Ewy, & Watson, 1982). However, it has been often overlooked by researchers in this community. Great strides have been made in the understanding of infant attention over the past several decades. In the section that follows, I briefly review that progress, and then turn back to a description of how that progress is relevant to some prior work on infant contingency perception.

The Development of the Synchronous Reinforcement Paradigm. The basic paradigm was derived from early work I had done with Robert Bundy on infant auditory function. In 1981, we developed a procedure to try and measure infants' preference for different auditory stimuli. In this paradigm, we provided the infant with two identical visual targets to the left and right of midline. In one study, the presentation of one auditory stimulus was made contingent upon infants' fixation to one of the visual targets, and another auditory stimulus was presented contingent upon fixation to the other visual target. In this way, differential fixation of the two targets could be taken as an index of the infant's preference for the contingent auditory stimulus. In these studies, we observed a strong visual preference for targets where fixation was associated with the presentation of a female voice. This occurred whether the voice was

paired with no other auditory track, or with white noise (Colombo & Bundy, 1981). In subsequent work, we established that one could familiarize infants with a particular auditory stimulus, and then test for the infant's preference for the familiar or a novel auditory stimulus. We found evidence for both systematic familiarity and novelty preferences in the auditory modality, depending on the age of the infant and amount of familiarization that the infant received with the auditory stimuli prior to the test (Colombo & Bundy, 1983). We eventually extended the work to sequential tests with multiple auditory stimuli, and established 4-month-olds' preferences for spectrally rich tones (Colombo, 1985).

We then adapted this procedure to address hypotheses about infants' preferences for the acoustic properties of "motherese" (e.g., Fernald, 1985; Fernald & Kuhl, 1987; Fernald & Simon, 1984). Interestingly enough, we were unable to confirm infants' preferences for the exaggerated frequency-modulated sweeps that were presumed to be the basis for infants' attention to such speech (Colombo & Horowitz, 1986). Our null findings were dismissed early on, and were attributed to the insensitivity of the paradigm. In some ways, this was productive, as it spurred our work on to another direction. I note here with some degree of satisfaction that several more recent attempts to demonstrate infants' preferences for such acoustic properties in isolation have also yielded null findings (Cooper, Abraham, Berman, & Staska, 1997; Cooper & Aslin, 1994).

The new direction for this work came about as a result of viewing the auditory paradigm as an operant procedure. Essentially, the presentation of the auditory track could be conceptualized as reinforcement for fixating a particular stimulus. Rovee-Collier (e.g., Rovee & Rovee, 1969) had constructed a comprehensive research program built upon a "conjugate reinforcement paradigm," where the intensity of the response (strength of footkick) was associated with the intensity of the reinforcement (degree of movement of mobile elements). In our procedure, however, the presentation of the reinforcement was "synchronous" with the response (see Ramey, Hieger, & Klisz, 1972); that is, although neither the response nor the reinforcement varied in intensity, the onset and offset of the auditory track was associated with onset and offset of the

fixation response. As such, we thought this procedure might thus hold some promise as a paradigm for studying early learning. Indeed, in a series of early implementations, we found the learning paradigm to be surprisingly powerful, and other laboratories that have published with the procedure (e.g., Coldren, 1997; Tyrrell, Zingaro, & Minard, 1993) have reported similar effects. Given the themes explored previously in this paper, one is tempted to attribute this to the high degree of temporal correlation between response and consequence. That is, in the synchronous reinforcement paradigm, two distinct temporal cues are presented for the infant: the onset of reinforcement is synchronous with the onset of the operant, and the offset of reinforcement is synchronous with the termination of the operant. It is possible that the high degree of temporal redundancy is a factor that makes such a task easily adapted to the testing of even very young infants.

Stimulus and Positional Cues in Infant Learning. In a set of four experiments (Colombo, Mitchell, Coldren, & Atwater, 1990), we examined the ability of 3-, 6-, and 9-month-olds to learn the association between an auditory stimulus (i.e., auditory reinforcement) and infants' attention to visual/spatial displays. Here, we were primarily interested in reinforcing infants for fixating a checkerboard or a bull's-eye in a standard ABAB design with lagged baselines. The lateral position of the stimulus alternated from trial to trial, and so we thus reinforced a particular target, irrespective of its lateral position. The target that we chose to reinforce was one that the infant indicated as a non-preferred one during a baseline period. One of the problems we encountered in designing this study, however, was that we did not have a good "control" condition for evaluating whether infants were actually voluntarily fixating the reinforced target, or whether their looking was tropistically "captured" by the onset of the auditory stimulus. What we decided to do was to include a condition in which infants were reinforced for fixating a particular lateral position, irrespective of the particular target that occupied it. In a series of complicated analyses, we could then compare responses to the target under conditions where looking to the target was reinforced against responses to the target and where an equivalent amount of reinforcement was present, but where such reinforcement was not contingent upon looking to the target.

To our surprise, the inclusion of this design feature produced the most interesting findings of the study. We were able to show that infants of all ages learned both the stimulus and positional contingencies (see Figures 1 and 2).

However, there were hints of important differences among the ages in the responses to the two types of contingencies. The 3-month-olds showed somewhat faster learning of the positional contingency and somewhat slower learning of the stimulus contingency, although these differences did not attain significant differences. In addition, when we imposed a 5-minute delay between training and an extinction probe, we found that this youngest age group retained the positional cue, but did not retain the stimulus cue. In two final experiments, we confounded the stimulus and positional cues during training, and dissociated them during the test, and the results were strikingly clear: both of the older age groups acquired the association between the reinforcer and a target, while the 3-month-olds acquired the association between the reinforcer and a lateral position (see Figures 3 and 4).

Initially, given that these conditions were simply included as design features, we did not have any theoretical basis for expecting these results. Indeed, the article makes reference to Sherrington's (1906) interoceptive/exteroceptive dichotomy, but the careful reader will recognize this as a post-hoc rationale.

Figure 3

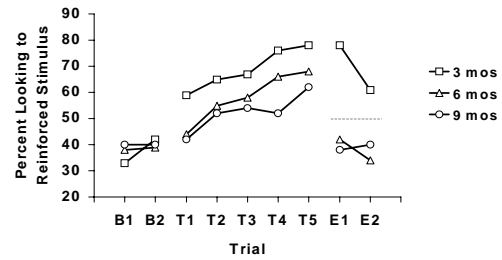
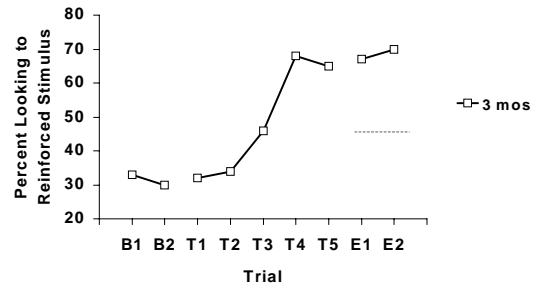


Figure 4



However, recent work on the development of the brain systems that subsume attentional function in infancy (see Colombo, 2001, for a review) seem to provide a clearer rationale for the findings. Functions related to spatial orienting are attributable to the operation of the posterior (or "where") attentional system, while functions related to orienting to object features are attributable to the operation of the anterior (or "what") attentional system. Table 1 shows that functions related to spatial orienting develop rapidly from about 8 weeks to 4 or 5 months of age. Attention to object features, however, follows a developmental course that begins somewhat later, and extends into the latter half of the first year. As such, what we were probably seeing in Colombo et al. (1990) with respect to positional and stimulus cues from 3 to 9 months was a developmental shift from the dominance of systems that serve spatial orienting to those that serve orienting to objects and object features.

Figure 1

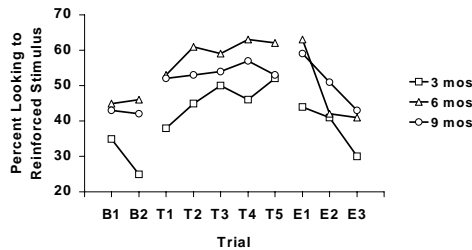


Figure 2

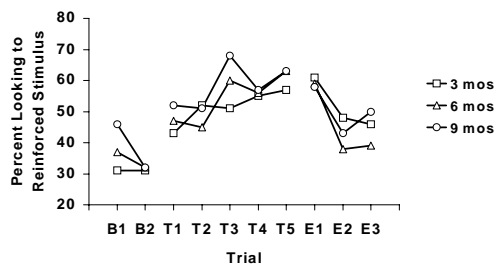


Table 1

Development of components of visual attention and orienting (adapted from Colombo, in press).

Global Attentional Function	Attentional Subcomponent	End of Devel. Course
Alertness	Attain/Maintain alert state	12 weeks
Spatial Orienting	Smooth Pursuit	16 weeks
	Fast Saccades	8 weeks
	Disengagement	16 weeks
	Inhibition of Return	26 weeks

	Color/Form Compounds	20 weeks
Attention to Object Features	Intrastimulus shifts	10 weeks
	Object Cue Dominance	26 weeks
	Interstimulus Shifts	26 weeks
Endogenous Attention	Sustained Attention	into toddlerhood

This interpretation is bolstered by a more recent report published by Harman, Posner, Rothbart, and Thomas-Thrapp (1994). In this study, 3-, 6-, and 9-month-old infants were observed orienting to novel objects at novel spatial locations. Location and object novelty were equally attractive to 3-month-olds, but 6- and 9-month-olds responded more strongly to novel visual stimuli than to novel locations.

Conclusions and Implications

What I hope to have accomplished here is to show that very simple properties of CNS response may lie at the core of contingency perception. The brain processes inputs in a distributed and parallel way, but reassembles such inputs as a function of its ability to detect correlations among those inputs across space and time. Furthermore, I hope that I have made it clear that an understanding of the development of the neural pathways that underlie basic cognitive functions during infancy is useful in understanding age shifts the perception and processing of contingencies. A grasp of the developmental cognitive neuroscience literature will be useful in the ability of researchers to posit credible and parsimonious hypotheses about early learning.

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