A. Specific Aims

Given the general and fundamental importance of sequential order skills across so many domains of behavioral functioning, the current project will investigate the development of serial order skills from infancy up to 5 years of age. The project is broadly conceived within a dynamic systems perspective and is guided by a model that makes 3 specific assumptions: (1) that multimodal redundancy facilitates serial order processing, (2) that initially in development response to serial order is governed by bottom-up perceptual processes that search out the surface spatiotemporal structure of serially ordered events, and (3) that as development progresses, the balance shifts to control by top-down, cognitive processes that focus primarily on the meanings inherent in events. Based on this model, the specific aims of this project are to investigate: (1) the role of multimodal redundancy in the processing of serial order across development, (2) the separate and combined contribution of temporal and spatial sensory attributes to the perception of serial order in infants and children, (3) the developmental emergence of responsiveness to event meanings and its effect on the perception of serial order per se, and (4) the very process of sequence learning through the application of microanalytic techniques designed to uncover the dynamic, moment-to-moment changes in serial order learning as a function of multimodal redundancy, response time requirements (free or speeded response), and cognitive set (implicit or explicit knowledge of serial order information).

B. Background and Significance

Theoretical Significance of Serial Order. It is difficult to escape the pervasive and ubiquitous influence of serial order in everyday life. For example, language, music, dance, sporting activity, and social interaction all depend critically on the serial ordering of the discrete actions that comprise them. The specific sequential arrangement of the discrete actions that constitute such complex behavioral acts imbues them with an overall meaning that transcends the characteristics of the individual acts or stimulus elements that make up the complex acts (Baldwin & Baird, 2001; Fraisse, 1982; Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003; Lashley, 1951; Terrace, 1993; Zacks & Tversky, 2001). For example, a given series of notes can have very different musical meanings depending on their specific sequential arrangement (Fraisse, 1982). Likewise, the phrase: "the boy swiped against the tree" has clear meaning, but the phrase: "the tree swiped against the boy" is at best ambiguous.

Development of Serial Order Processing. Despite the lack of studies that investigate infants' sensitivity to distant serial order relations, developmentalists have appreciated the importance of sequences for infants. Piaget (1952) proposed that serial order skills first appear in development during the fourth stage of sensorimotor development, somewhere between 8 and 9 months of age. He noted that it is at this age that infants first become capable of stringing together familiar but distinct action patterns into a series of actions that provide the means to an end. He interpreted this newly emerging ability as a reflection of concurrent elaborations in the infant's mental capacities needed to support the production of sequentially organized actions. These mental capacities include the ability to perceive and produce sequences that are independent of the infant's own actions. In other words, according to Piaget, it is at this point in development that infants can for the first time represent serially ordered sequences as independent properties of their external world and become capable of recombining a series of actions into novel sequences. The issue of sequence perception has been largely dormant until recently when investigators interested in the cognitive underpinnings of event perception have begun to wonder about the contribution of sequential structure to infants' comprehension of events. For example, Baldwin and Baird (2001) posed the following fundamental question: "When observing others in action, do infants experience an incomprehensible flow of movement, or are they skilled at finding relevant structure in the behavior stream?" In other words, can infants parse continuous actions into meaningful chunks? Baldwin and Baird pointed that out that adults can easily extract the specific meanings and intentions of other people from the sequential structure of their actions and proposed that our knack for "reading" other peoples' intentions is mediated by a generative knowledge system that discerns intentions in actions based specifically on the sequential organization of actions. If that is the case, then this knowledge system is likely to depend on the developmentally earlier emergence of the ability to parse the surface characteristics of sequentially organized events (Conway & Christiansen, 2001). Indeed, recent studies from the PI's laboratory (Lewkowicz, 2004) indicate that the ability to parse the surface characteristics of sequentially organized events emerges as early as 4 months of age.

Infant Sensitivity to Temporal and Spatiotemporal Information. If perceptual serial order skills emerge as early as 4 months of age then it would be reasonable to expect that they emerge from an initial sensitivity to the temporal aspects of sensory input. In fact, there is substantial evidence that infants are sensitive to various forms of temporal information, both in the auditory and visual modalities (Lewkowicz, 1989; 2000). Beginning at birth (Gardner, Lewkowicz, Rose, & Karmel, 1986) and thereafter (Lewkowicz, 1985a, 1985b, 1994) infants exhibit differential responsiveness to temporally distributed stimulation. In addition, infants can: (a) perceive the temporal organization of a sequence of identical (Demany, McKenzie, & Vurpillot, 1977) and distinct (Chang & Trehub, 1977) sounds, (b) detect changes in the duration of the silent intervals that separate a series of sounds (Thorpe & Trehub, 1989; Thorpe, Trehub, Morrongiello, & Bull, 1988), (c) discriminate between different visual rhythms (Mendelson, 1986), (d) form expectations based on the temporal distribution of stimulation (Canfield & Haith, 1991), (e) anticipate a change in the temporal distribution of stimulation (Brooks & Berg, 1979; Clifton, 1974; Davies & Berg, 1983; Donohue & Berg, 1991), and (f) usually exhibit relatively precise temporal interlocking in their interactions with adults (Jaffe, Beebe, Feldstein, Crown, & Jasnow, 2001; Lester, Hoffman, & Brazelton, 1985; Stern, Beebe, Jaffe, & Bennet, 1977). In addition to these various temporal sensitivities, recently the PI and his collaborators at the California Institute of Technology (Scheier, Lewkowicz, & Shimojo, 2003) have discovered that infants also possess a particularly impressive sensitivity to the spatiotemporal relations between auditory and visual inputs. We have found that the ability to detect specific spatiotemporal relations becomes so well-refined by 6 months of age that from this age on infants exhibit evidence of an audiovisual illusion previously found in adults (Sekuler, Sekuler, & Lau, 1997). Thus, when infants watch two identical visual objects move past one another, 6- and 8-month old, but not 4-month-old, infants respond to the objects as if they were bouncing against one another, but only when they hear a sound precisely when the objects coincide in space and time.

Infant Sensitivity to Sequential/Serial Structure. As already noted, prior to our studies of infants' detection of serial order, no infant studies explicitly tested whether infants are sensitive to the specific serial order of sequentially organized events. As a result, the findings from available studies do not permit any inferences regarding infants' ability to perceive sequential organization per se. The evidence to date indicates that infants can: (a) perceive word order (Mandel, Nelson, & Jusczyk, 1996), (b) learn to move a series of mobiles and remember the order in which they moved them 24 hours later (Merriman, Rovee-Collier, & Wilk, 1997), (c) learn the transitional probabilities between adjacent members of a sequence of speech sounds (Aslin, Saffran, & Newport, 1999), and (d) learn, remember, and reproduce multi-act sequences in the correct order (Bauer, Wiebe, Waters, & Bangston, 2001; Carver & Bauer, 1999, 2001; Wenner & Bauer, 1999). All of these findings suffer from interpretive problems vis-à-vis serial order detection. Thus, the finding that infants perceive word order is questionable because the overall prosody of the sentences in which the words were embedded differed and, according to the authors, most likely accounted for the positive findings. The finding that infants can remember the order in which they kicked a series of mobiles does not provide direct evidence of serial order skills because memory for the specific ordering of the mobiles actually depended on priming with the directly preceding mobile (Gulya, Rovee-Collier, Galluccio, & Wilk, 1998), suggesting learning of adjacent pair relations. Infants ability to learn the transitional probabilities between the adjacent members of a sequence of speech sounds also can be interpreted as learning of adjacent relations. Finally, the findings reported by Bauer and her colleagues clearly show that infants can encode the order of a series of actions and reproduce them later but because order was not directly manipulated, it cannot be determined if infants were aware of the specific ordering of component actions.

D. Research Design & Methods

D1a. Experiment 1 - Perception of Serial Order in the Absence of Relative Spatial Cues

To begin our investigation of the separate role that temporal and spatial cues might have played in our initial study (Lewkowicz, 2004), Experiment 1 will investigate infants' response to an event devoid of spatial cues linking the different objects. In other words, the events presented here will consist of objects that will be seen and heard moving one at a time in the absence of the other objects and their sounds.

Participants. As in our initial study (Lewkowicz, 2004), we will test separate groups of 4- and 8-month-old infants. In this experiment, we will test 48 4-month-old infants and 24 8-month-old infants, balanced for gender at each age. All infants will be fullterm and healthy at the time of birth and will have had no history of visual or auditory problems prior to test.

Apparatus & Stimuli. A PC computer will be used to display multimedia movies in which the same stimuli seen in Fig. 10 will be seen moving and in which each of them will make the same impact sounds heard in our previous studies (Lewkowicz, 2004). The same computer will be used to record infants' visual behavior in response to the movies. The test session will be videotaped for further analyses and for computation of interobserver reliability.

Procedure. A trial will begin with the appearance of an object at the top of the screen. Then, the object will move down, make a visible and audible impact against a visible surface, move off to the right, and then disappear. Once this object disappears from view, the next object in the series will appear and then move in the same fashion as the first object (making an impact sound along the way). Finally, once the second object disappears, the third object will appear and perform the same action as the first two objects. The motion velocity of all three objects will be identical. Thus, this method of stimulus presentation will insure that infants see only one object at a time and hear its associated sound in the absence of the other two objects. Recall that in our original study the 4-month-old infants only detected serial order changes if the local A-V synchrony part of the event was blocked from view. Because we do not know whether this aspect of the event will play a role here, we will test for it. To do so, we will habituate and test half the 4-month-olds with this part of the event being visible and the other half with this part blocked. Because the 8-month-old infants successfully discriminated order changes regardless of whether the A-V synchrony part of the event was blocked or not, the older infants will be tested only with the unblocked version of this event.

This, and all other infant experiments will employ the infant-controlled habituation/test procedure. Each trial will begin with the infant's look at the stimulus display and end either when the infant looks away for more than 1 s. or when the trial will reach some maximum duration (between 50-60 seconds depending on the experiment). Habituation trials will continue until the difference between the duration of looking during the last 3 habituation trials falls below 50% of the duration of looking during the first 3 habituation trials. An attention-getter (an unrelated stimulus) will appear on the screen in-between trials to capture the infant's attention back to the screen.

The actual experiment will begin with a Pre-test trial during which a segment of a cartoon will be presented to measure the infant's initial level of attention. The habituation phase will then follow and will continue until the habituation criterion is met. The test phase will then follow during which each infant will be given 4 separate test trials. The experimental design of the test phase will conform to the design shown in Table 1 in section C. As can be seen, there will be two different habituation-order groups at each age,. Thus, half the infants at each age will be habituated to the ABC stimulus order and the other half will be habituated to the CAB ordering. Then, each infant will be given an F test trial first followed by separate test trials during which the auditory, visual, and audiovisual attributes of order will be changed. The experiment will end with a single Post-test trial during which the same cartoon segment presented in the Pre-test trial will be presented again. Looking during the Post-test trial will be compared to looking during the Pre-test trial as well as to looking during the F test trial to rule out fatigue effects. Lack of fatigue will be indicated by maintenance of similar levels of looking in the Pre- and Post-test trials and by a significant response recovery in the Post-test trial relative to looking in the F test trial.

Analyses & Predictions. Although the infant-controlled habituation method insures that every infant reaches the habituation criterion, and despite the fact that analyses of the habituation data from our initial studies have indicated that habituation profiles (i.e., slopes) did not differ in the two age groups, we will still examine the habituation data. The events to be presented here will be different enough that it is possible that they may produce different habituation profiles. The test trial data will be subjected to 2 separate analyses. One will compare responsiveness in the 2 age groups in the visible A-V synchrony condition. The other will compare responsiveness of the 4-month-olds in the visible and invisible A-V synchrony conditions. In the first case, the analysis will be a repeated-measures, mixed analysis of variance (ANOVA), with age, habituation group, and test trial order as between-subjects factors and test trial type as the within-subjects factor. This analysis will then be followed up with planned comparison tests, comparing the duration of looking in the order-change test trials versus the duration of looking in the F test trial to determine whether infants exhibited significant response recovery in any of these test trials (i.e., whether they detected the difference). The second analysis will be identical except that age will not be one of the factors. Given that temporal-only serial order is more difficult to perceive (Gower, 1992), it is possible that detection of the serial order differences here may be more difficult. It is also possible that this effect may be differential across age. That is, the younger infants may not exhibit successful detection even if the order differences are multimodally specified whereas older infants might perceive them but only if multimodally specified. This scenario would be interesting from an intersensory redundancy point of view by showing that the developmental window for when a multimodal redundancy advantage has its maximal effects shifts depending on the difficulty of the task. This possibility has so far not been explored in infant research (Lewkowicz & Kraebel, in press).

D1b. Experiment 2 – Perception of Isochronous, Spatially Static Serial Order

The majority of experiments on serial order learning and memory (Terrace & McGonigle, 1994) present subjects with spatially static, concurrently visible objects and the subject's task is usually to perform some sort of sequential motor task related to the objects (e.g., touching them in a given order). Adult subjects are much less dependent on the dynamic properties of stimulation than are infants (Kellman & Arterberry, 1998) and, thus, it is not surprising that they exhibit such serial order learning abilities. As noted above, infants depend much more on dynamic cues for event perception. Thus, it is possible that the temporal cues generated by the objects' motion and their spatial arrangement in our original studies may have played an important role in their successful detection of serial order. It is important to emphasize here that this does not mean that infants are not capable of sequence learning in the absence of motion cues. Smith and colleagues have already shown that infants can learn sequences composed of static stimuli (Smith, Loboschefski, Davidson, & Dixon, 1997). The problem is that Smith et. al. did not manipulate stimulus order and, thus, their studies do not answer the central question of interest in this proposal, namely, whether infants are sensitive to the specific serial order of a set of items and, thus, whether they possess the kinds of serial order abilities defined by Lashley.

Participants. Separate groups of 4- and 8-month-old infants (24 infants/age) will be tested.

Apparatus & Stimuli. The apparatus & stimuli will be the same as in Experiment 1.

Procedure. This experiment will be an analogue of the typical adult serial order learning experiment but rather than requiring infants to make sequential motor responses we will use the habituation/test procedure. Thus, on each trial infants will see the objects shown in Fig. 10 but this time all the objects will be visible in different parts of the screen and their serial order will be defined by their sequential zooming and sounding behavior. For example, at the start of a trial the circle will gradually double in size, make its sound as it reaches its maximum size, and then return to its original size (this will take 1 s.). Half a second later, the triangle will do the same, and half a second later the square will do the same. Then there will be a 1 sec. interval during which the objects will remain static at their original size. This sequence will be repeated over and over again for the duration of the trial. The intra-sequence intervals in this experiment will be identical (.5 sec), thereby creating a temporally isochronous sequence. The types of test trials presented here can be seen in Table 1.

Analyses & Predictions. The same ANOVA outlined for Experiment 1 (including age as a between-subjects factor) and appropriate planned comparison tests will be conducted here. It is possible that the younger infants' failure to respond to the auditory and visual order changes was because objects' motion caused a kind of temporal "smearing" and prevented them from getting a "good look" at the serial ordering of the objects. In other words, in order for infants to succeed in this task they need to be able to encode the objects' specific featural characteristics. The objects' motion may have prevented clear access to these. Of course, this explanation does not apply to the auditory order changes, but the fact that 4-month-olds did successfully discriminate order when it was bimodally specified suggests that these infants could overcome poorer visual event specification through multimodal redudancy. Thus, we predict that the less dynamic nature of the events in this experiment will actually facilitate the perception of serial order and that infants at both ages will be able to detect all 3 types of order changes.

D1c. Experiment 3 – Perception of Rhythmic, Spatially Static Serial Order

As indicated in Sections B and C, infants are sensitive to rhythmic structure, particularly if it is audiovisually specified. What has not been tested so far, however, is whether infants' sensitivity to rhythmic structure can be put in the service of other types of perceptual/cognitive functions such as, for example, serial order perception and learning. We hypothesize that imposing temporal structure onto an audiovisual sequence will facilitate the perception of serial order. Such a demonstration would provide important new developmental evidence in support of one of the classic and enduring issues in perceptual psychology: the problem of scene analysis (Bregman, 1990; Fraisse, 1982; Gibson, 1966; Lashley, 1951). In essence, the problem is to explain how it is that we somehow end up with perceptually unified and cognitively meaningful representations of physical reality when our senses receive a continuous stream of concurrent multimodal inputs. For some, like Gibson (1966), it is not necessary to posit any internal perceptual/cognitive organizational mechanisms because the external sensory array is already structured and the job of the perceptual system is simply to pick up that structure. For others, perceptual and neural processes must actively synthesize the internal representations of reality and extract their meanings (Bregman, 1990; Lashley, 1951). Of course, in addition to being perceptually and cognitively inexperienced, an infant's nervous system is still quite immature and, thus, it may not be fully capable of synthesizing internal representations sufficiently enough to extract their meaning. Given this state of affairs, a developmentally early demonstration of the ability to extract sequential information would suggest that direct perceptual processes have developmental primacy.

Participants. We will begin with groups of 2-, 3-, & 4-month-old infants (N=24/age) and add older infants if results do not conform with expectations to determine when this ability first emerges.

Apparatus, Stimuli, & Procedure. The apparatus & stimuli will be the same as in Experiment 1. The procedure will be the same as in Experiment 2 except that the interval between the zooming behavior of the second and third object will be double the interval between the first and second object and the inter-sequence interval will be double the duration of the longer intra-sequence interval. The types of test trials presented here can be seen in Table 1.

Predictions. We expect that rhythmic structure will facilitate serial order perception and that this will be evident in the emergence of successful discrimination even before 4 months of age. Based on Assumption # 3, we also anticipate that the earliest successful discrimination will be to multimodal order changes. If rhythmic structure does facilitate serial order detection at the younger ages then we will conduct additional experiments to investigate whether complexity affects performance. This will be done by increasing the number of objects/sounds and the rhythmical complexity of the sequence. We expect to find a performance by complexity interaction.