HEART RATE RESPONSES AND HEART RATE RHYTHMS, AND INFANT VISUAL SUSTAINED ATTENTION

John E. Richards

INTRODUCTION

''Pay attention to me!'' A recalcitrant child in the ''terrible twos'' often hears this admonishment from her parents. This admonishment shows that parents assume that children at young ages can direct their attention in a voluntary fashion and respond to verbal instructions. But what about getting a much younger child to ''pay attention''? When do children first begin to attend to the sights and sounds of their world? When can a child direct its attention voluntarily to interesting stimuli? Parents often use special methods to elicit attention in young infants, e.g., cooing, making faces, playing, and even talking to infants. This parental behavior implicitly assumes that the infant is able to direct her attention to specific stimuli at a very early age.

When does an infant start attending to environmental stimulation? How does one attract the attention of an infant? What types of things do they prefer to look at, and for how long? These are questions that psychologists have asked for several years about the attentional processes of infants. Moreover, attention to a stimulus is one indicator that the infant can discriminate the stimulus from its

Advances in Psychophysiology, Volume 3, pages 189–221.

ISBN: 0-89232-908-4

surroundings or from previous stimuli. Therefore, various measures of attention have been used as dependent variables in studies of psychological processes in the infant. Psychophysiologists have contributed to the study of infant attention in several ways. Most notably, however, was the discovery by psychophysiologists that heart rate (HR) is closely associated with attention in infants. Thus, many studies of infant attention have used HR responses in behavioral tasks as a measure of ongoing attention.

HR has been postulated to be related to at least three phases of ''attention'' in the young infant (cf. Graham, 1979, and Graham et al.. 1983, with Porges, 1976, 1980). The first phase is a ''transient-detecting interrupt system'' (Graham, 1979). This system detects a change in the environmental array and interrupts the information processing system to alert it that action may be necessary. The HR response controlled by this system is brief, lasting less than one second, and its nature is stimulus dependent. The second phase of information processing is the ''orienting reflex'' (OR). Its purpose is to evaluate the novelty of the stimulus and perform some preliminary processing of the information in the stimulus. The OR is phasic in nature, lasting only about 5 or 6 s. The level of the HR OR is related to the relative novelty of the stimulus. The transient detection system and the OR are reflexes and, once elicited, generally follow the same time course regardless of subsequent input. Both of these systems can be controlled by the mechanisms of selective attention. The reader is referred to Graham (1979) or Graham et al. (1983) for further discussions of these attentional phases.

The third phase of infant attention that may be related to HR is sustained attention (Porges, 1976, 1980). This type of attention is for the actual cognitive processing of information contained in the stimulus. This phase follows the initial ''tests'' of the stimulus and maintains or amplifies the HR OR response in order to continue active processing of the stimulus. This phase not only involves changes in HR, but also results in decreased HR variability, smaller respiration amplitude, and inhibition of body movements, among other changes. This phase is voluntary, i.e., under subject control, and thus its characteristics are more complexly determined than the other two phases. Individual differences are more interesting at this level than at the reflexive levels of processing, since sustained attention requires active, *subject-controlled* cognitive processing. This phase of attention has not been studied as extensively by psychophysiologists interested in infant behavior and development, perhaps because of the lack of theoretical models and empirical manipulations which distinguish it from the reflexive aspects of infant attention.

The studies presented in this chapter represent my first efforts toward studying sustained attention in young infants. In the next section, the use of HR as a measure of infant attention will be briefly summarized. Then, a rhythmic variation in HR levels that reflects the influence of respiration will be described: respiratory sinus arrhythmia (RSA). The infant's RSA level may predict the infant's ability to engage in sustained cognitive processing of interesting stimuli. Following those two sections, a new technique will be described for the measurement of infant sustained attention, and the results of several studies will be presented that have used this method to examine sustained attention. Individual differences in sustained attention should be predictable by (or related to) the level of RSA measured in baseline recording. It has also been hvpothesized that the amount of cognitive effort is reflected in the magnitude of task-induced changes in the autonomic nervous system (Kahneman, 1973). Therefore, the level of sustained attention should be positively correlated with changes in HR that occur during attention tasks, and the results of several studies bearing on this hypothesis will be discussed.

HEART RATE RESPONSES: THE ORIENTING REFLEX

The orienting reflex (OR) was described by Sokolov (1963) as a response to perceived change in environmental stimulation. The OR became interesting to developmental psychologists through the seminal article of Graham and Clifton (1966). This article integrated the sensory intake/rejection hypothesis of the Laceys (e.g., Lacey, Kagan, Lacey, & Moss, 1963) with the OR and the defensive reflex (DR) as postulated by Sokolov. The OR/DR distinction paralled the intake/rejection distinction, and therefore both were indicated by directional HR changes. Most important to developmental psychologists was that a DR could be indexed with HR acceleration whereas an OR could be indexed with HR deceleration.

Research using HR with infants proceded along two directions following the Graham and Clifton article. The majority of the researchers adopted the assumption that differential HR changes indicated the occurrence of either an OR or a DR. Thus, for example, HR deceleration has often been used as the dependent variable in habituation-dishabituation paradigms, with HR deceleration in the dishabituation phase leading to the inference that stimulus discrimination had occurred (e.g., Appel & Campos, 1977; Kinney & Kagan, 1976). The bidirectional nature of the HR response led to the use of HR acceleration as an index of emotional distress, such as stranger anxiety (Campos, Emde, Gaensbauer, & Henderson, 1975), and fear of the visual cliff (Campos, Langer, & Krowitz, 1970; Richards & Rader, 1983; Schwartz, Campos, & Baisel, 1973). The reader may refer to a review by Von Bargen (1983) for further information about this use of HR research in infants. The primary interest in these studies was not in HR itself, but in other psychological phenomena.

The second line of research has assessed the validity of the hypothesis advanced by Graham and Clifton (1966). Much of this work has been done by Frances Graham, Rachel Clifton, and Keith Berg, and their students and coworkers. This line of research has investigated HR deceleration and acceleration as indices of the OR and DR, respectively. The phasic HR changes occuring from about 1 to 7 s following stimulus onset meet the requirements set forth by Sokolov (1963) for an OR and DR (Graham, 1979). This work has been reviewed several times (Graham, 1973, 1979; Graham, Anthony, & Zeigler, 1983; Graham & Jackson, 1970).

The infant HR response studied within this latter tradition is a phasic reflex to novel stimuli. This is shown by several considerations. First: once the response is elicited, it continues on the same time course independently of whether or not the stimulus remains present. Several studies have used 2 s auditory stimuli and elicited an OR (Graham et al., 1970) which shows a peak HR deceleration near 3 or 6 s and a return toward prestimulus levels by about 8 or 9 s. Stimuli of other durations (5, 6, 10, 20, 30 s) elicited nearly identical HR responses. Second: the time courses of the OR and DR for HR are nearly identical (Berg, 1975; Clarkson & Berg, 1983; Kearsley, 1973). This similarity in the time course is a reflection of their reflexive nature, and may imply that they are mediated by similar brain mechanisms. Third: the time course for offset HR responses is nearly identical to that of the onset response. The offset response is often thought of as an OR to the absence of a stimulus. The offset responses of infants generally follow the same temporal pattern as the OR response, although they are usually weaker in amplitude (Adkinson & Berg, 1976; Berg, 1972, 1974; Brooks & Berg, 1979; Lewis, 1971). The similarity between the onset and offset HR response implies that the reflex occurs in the absence of a stimulus. Finally: the OR response is not elicited by every stimulus occurrence. It is only elicited for relatively novel stimuli, implying that a prior stage of information processing must exist, which informs the system about the relative novelty (mismatch) of the stimulus. Once elicited, however, the HR OR continues on its course with little regard to environmental conditions.

HEART RATE RHYTHMS: RESPIRATORY SINUS ARRHYTHMIA

Between 1969 and 1975 a number of researchers attempted to show that the OR, as measured by HR deceleration, existed in newborn infants. Several studies by Porges and his associates determined that newborn infants showed larger HR responses if they had high HR variability than if they had low levels of HR variability (e.g., Porges, 1974; Porges, Arnold, & Forbes, 1973; Porges, Stamps, & Walter, 1974). This led to the hypothesis that the level of HR variability measures individual differences in attentional responsivity of the infant (Porges, 1974, 1976, 1980), or even of older children and adults. More recently (Porges et al., 1982), it has been argued that it is not HR variability per se that is related to attentional responsivity. Rather, it is HR variability caused by respiratory rhythms (i.e., RSA) that is related to individual differences in attentional responsivity. It has recently been confirmed that it is RSA, rather than overall HR variability, that is related to infant attentional patterns (Richards, 1985a, 1985b) as well as to infant visual memory (Linnemeyer & Porges, 1986). Neonatal RSA is also partially predictive of developmental outcome at 8 and at 12 months of age (Fox & Porges, 1985). This hypothesis has led Porges, myself, and several others, on an exploration of the relationship between RSA and attention.

What is RSA? It is first an empirical description of a systematic rhythmicity in HR that coincides with respiration phases. The inspiratory phase of respiration is usually followed by an increase in HR level, the expiratory phase by a decrease. The physiological mechanism(s) causing RSA is under some debate. Nevertheless it has been established that the HR changes resulting from RSA are mediated through the vagus nerve and thus are controlled by the parasympathetic branch of the autonomic nervous system, not by the sympathetic branch (Anrep, Pascual, & Rossler, 1935; Katona & Jih, 1975; Porges et al., 1982). There is evidence that the level of influence of the vagus nerve on cardiac activity is paralleled by the level of RSA, leading to the claim that RSA is an estimate of "vagal tone" (Porges et al., 1982).

In addition to its possible role as an estimate of vagal tone, RSA may also measure the general functional level of brainstem mechanisms. RSA is mediated via the respiratory centers of the brainstem (Grossman, 1983; Lopes & Palmer, 1976; Spyer, 1979). Respiration afferents send information to the respiratory centers regarding the size of the lungs (stretch afferents) and the phase of the cycle. The respiratory centers via efferent connections inhibit the vagus during the inspiratory phase of the respiratory cycle, allowing HR to increase due to the lack of vagal inhibition via cardiac efferents. The respiratory centers send no inhibitory messages to vagus during the expiratory phase of the respiratory cycle, which results in HR slowing due to the inhibition of HR by the vagus. Thus, the rhythm of RSA is due to the functioning of the brainstem respiratory centers. Presumably, a well-functioning brainstem would result in more efficient slowing and speeding of HR, leading to larger magnitude RSA, when compared to a poorly-functioning brainstem. RSA therefore may be an index of the functioning of the brainstem respiratory centers rather than primarily an estimate of vagal tone.

Why is RSA related to infant attentional responses? Porges (Porges, 1976, 1980) has argued that attention processes are facilitated by cholinergic activity in the central nervous system, which inhibits ongoing behavior and allows the focusing of attention. This facilitation may be particularly relevant for "sustained" attention, since sustained attention involves the inhibition of motor movement. Individual differences in sustained attention therefore could be measured if one has an adequate measure of the "cholinergic nervous system." Porges argued that since RSA is an estimate of vagal tone, it is also an measure of the strength of cholinergic activity in the CNS, since vagal control of the heart is mediated by acetylcholine. Therefore, RSA should also predict individual differences in sustained attention. Presumably, this should not be limited to HR responses, but be related to other components of attention, such as visual fixation.

An alternative explanation for the relationship between RSA and infant attention responses is the role of RSA as an measure of brainstem integrity. It is reasonable to assume that high levels of RSA indicate a well-functioning brainstem respiratory center, which has proper respiration afferent input, proper cycling of respiration, efferents to respiratory muscles, and collaterals to control the level of vagal influence on HR. Damage to the respiratory center results in low levels of RSA, as well as irregular and pathological patterns of respiration, as in Respiratory Distress Syndrome (Kero, 1974) or neonatal hypoxia (Baker & McGinty, 1977, 1978). The brainstem is involved in the control of attention in several ways, such as the modulation of state activity, the control of levels of alertness, and by channeling efferent/afferent messages for peripheral systems (e.g., body movement) important for attentional behavior. It may be that RSA is related to sustained attention activity because it measures the relative functional integrity of lower brain processes, and individual differences in brainstem integrity. This hypothesis suggests a relationship between perinatal trauma resulting in disruption of brainstem functional integrity and poor developmental outcome.

The latter hypothesis is not being offered as a definitive reason for the RSA/sustained attention relationship, merely as a plausible alternative to invoking the constructs of "cholinergic nervous system" and "vagal tone." One can imagine empirical tests that would distinguish between these two alternative views, but such tests would be difficult. The antecedents and consequences of the normal range of individual differences in sustained attention, as well as in pathological populations, would be the same for both hypotheses. Either position may be plausible given the current empirical evidence.

How is RSA measured? Measures of RSA should provide a quantitative measure of RSA level and measure HR variability only at the frequency of respiration of the subject. Most measures of HR variability (e.g., variance, standard deviation, range) include variation in HR at several nonrespiratory frequencies, and therefore include variability due to sources other than RSA. Many so-called measures of high-frequency variability (e.g., successive differences mean square) are poor in this regard because the cutoff frequencies are often ill-defined (Wastell, 1981), and include variability at many undesirable (nonrespiratory) frequencies. The best indices of RSA may be obtained from spectral analysis techniques (Bohrer & Porges, 1982; Harper, Scalabassi, & Estrin, 1974; Womack, 1971). The power of the HR spectrum can be estimated at specific frequencies, and can be used to select variability in HR only at the frequencies of respiration for that subject. Spectral analysis techniques also provide an additional measure, coherence, which indicates the closeness of the fit between respiration and HR changes (Porges et al., 1981). Ideally, the frequency range of respiration for an individual subject should be empirically derived, and the frequency range for the spectral power of HR and its coherence with respiration should be chosen from that range. This is preferable to using either a hypothetical range, or an average range for that age group or subject type. Several other considerations for the use of spectral analysis methods for RSA can be found in Womack (1971), Harper et al. (1974), and more recently in Bohrer and Porges (1982).

HEART RATE CHANGES AND HEART RATE RHYTHMS: INFANT SUSTAINED ATTENTION

The studies presented in the remainder of this chapter were designed to experimentally examine sustained attention in young infants. Studies of infant visual attention have used the ''infant control procedure,'' fixed duration trials, or the ''visual preference method.'' The infant control procedure (Cohen, 1972; Horowitz, Paden, Bhana, & Self, 1972) involves the presentation of a stimulus for as long as the infant is fixating on it. The stimulus is terminated at the end of the infant's fixation. The measure of attention is the duration of fixation. However, one cannot be sure that the infant is actively attending during the length of fixation. Instead, fixation may be occurring without any active processing of the stimulus. This same criticism applies to methods using trials of fixed duration, since the infant may ''look'' without active processing. The visual preference method (Fantz, 1963) involves the presentation of two stimuli simultaneously and the length of fixation to each stimulus is recorded. In general, the stimuli differ on some dimension such as complexity, familiarity, the complexity of the perceptual process involved, and so forth. Differential looking time implies that the infant has the capability to discriminate the difference along the dimension of interest. It does not, however, measure the level of attention nor the quality of the underlying cognitive processes.

Recently, I have introduced a new method for studying infant visual attention. I have labeled this method the *interrupted stimulus* procedure. It is similar to the infant control procedure in that a stimulus is presented for as long as the infant fixates on it, and the stimulus is terminated when the infant looks away from it. However, in addition to this stimulus, a second stimulus is presented in the periphery in an attempt to distract the infant's attention from the primary visual stimulus. *Distraction time* is defined as the amount of time that the infant continues to attend to the central visual stimulus without being distracted by the secondary stimulus. The primary measure of attention in this paradigm is the distraction time.

The interrupted stimulus method may be superior to other techniques for measuring sustained attention in infants. The superiority is based on the concept of a ''limited information processing channel'' posited by information processing theory (Broadbent, 1958). Individuals are limited in the amount of external stimulation to which attention can be given. One operational measure of the amount of resources dedicated to a task (i.e., the level of attention given to the task) is the amount of time or the intensity of stimulation that is needed to distract the subject from the primary task. This method of using an interrupting stimulus to measure cognitive processing demands is quite common in research literature both with adults (e.g., Dawson, Schell, Beers, & Kelly, 1982; Wickens, Kramer, Vanasse, & Donchin, 1983) and with older children (Hagen, 1967; Hallahan & Reeve, 1980; Schiff & Knopf, 1985). This procedure is a better measure of information processing in the infant because it brings the termination of the fixation under experimental control, rather than allowing the infant to fixate on the stimulus without actively being engaged in cognitive processing of the stimulus. In the next sections several studies will be described using this new approach to measuring infant sustained attention.

LABORATORY PROCEDURES

Subjects

The subjects for the studies to be described were infants of three- to six-months of age. The infants were sampled cross-sectionally at 14 weeks (3 months), 20 weeks (4.5 months), and 26 weeks (6 months) of age. The infants were ''recruited'' by inspecting newspaper birth notices and contacting the parents to explain the study and obtain their participation. Only full-term infants with normal birth and healthy postnatal medical history were included in the studies. Infants who became fussy or non-alert during the experimental protocol were not included in the data analysis. It is known that state affects cardiac and behavioral responses of the infant, so the exclusion of non-alert and fussy infants increases the likelihood of obtaining optimal attentional responses during the experiments.

Baseline Respiratory Sinus Arrhythmia

The baseline measures of HR and RSA were taken during a 5-min period immediately preceding the presentation of the stimuli. The infant was seated on the parent's lap on a couch away from the experimental setup. The parent was instructed to keep movement to a minimum, but was not restricted from interacting with the infant. In general, the infant remained still on the parent's lap with a minimum of social interaction for two to three minutes, after which some fussiness began and parents engaged in some pacification of the infant. The infant's movement was not restricted.

The baseline measures of HR and RSA may have been contaminated by: a) social interaction, b) sleep state, and c) overall movement of the infant. However, it is assumed that the infants retain their relative standing on the baseline physiological measures, which may be used as measures of individual differences in attention.

Primary Stimuli

The primary (central) stimuli in the interrupted stimulus method have been a variety of patterns. The duration of the first uninterrupted look decreased from 14 to 26 weeks, so stimulus patterns were presented which the 26-week-old infants found sufficiently attractive to look at for several seconds on the first look. Originally (see Richards, 1985a), checkerboard patterns of varying complexity were used. The complexity levels of these patterns were chosen based on the theoretical analysis of visual preference behaviors of infants by Karmel and Maisel (1975). According to this model, the 6-month-old infants look for longer periods at the most complex level, the 4.5-month-olds at the intermediate levels, and the 3-month-olds at the simplest level. The increase in complexity preference with age should therefore be controlled by using the differing complexity levels. However, it was found that all of the infants looked longest at the intermediate complexity level, and that the decrease in looking time over this age range applied equally well to all three complexity levels (Richards, 1985a, 1985b). Therefore, as long as the stimulus resulted in visual fixation times of at least 5 to 10 seconds on the first uninterrupted look, it was deemed sufficient.

The patterns for Studies 1, 3, and 4 reported in this chapter were checkerboard patterns of varying complexity levels. In Study 2, only the medium complexity level check pattern was used, as well as a recording of a Sesame Street show, and a series of squares that increased and then decreased in size.

Interrupting Stimuli

The interrupted stimulus method as described in the introduction was an adaption of the primary/secondary task used in adult information processing research (e.g., Wickens et al., 1983). Rather than a secondary "task," the interrupting stimulus is merely presented in the infant's peripheral visual range. The first interrupting stimulus used was a single blinking LED at the side of the television screen that was used to display the primary stimulus. If the infant looked at the blinking light, a second set of LEDs, which blinked in a circular pattern, was presented to the side of the TV screen (Study 1). It was found in pilot testing that the circular pattern of LEDs did an acceptable job of interrupting the primary task, and was even more effective in sustaining the interruption. Thus, only the panel of blinking LEDs was used as the interrupting stimuli in studies subsequent to the first.

Quantification of the Physiological Data

The quantification of HR and RSA during the baseline period has been described in more detail elsewhere (Richards, 1980, 1985a, 1985b). The average HR level during the 5-min baseline period (HR) was also computed. Overall HR variability (HRV) was defined as the standard deviation on the 0.5- by 0.5-s HR values. Two measures of RSA were computed using spectral analysis techniques. The extent of RSA (XRSA) was defined as the sum of power of the HR spectrum at the frequency of the measured modal-respiration frequency for a 51.2 s epoch, and averaged over the five 51.2-s periods of the baseline. XRSA is very close in computation to the vagal tone measure ($\hat{V}$) used by Porges (e.g., Fox & Porges, 1985). The coherence of RSA (WCOH) was defined as the sum of the coherence over the same frequencies as XRSA, weighted by the power of HR at that interval (Porges et al., 1980). This measure can be described as the proportion of variability in HR at the respiratory frequency explainable by the HR-respiratory coupling. Other variables were recorded and computed, including low frequency HR variability, respiration rate, and respiration amplitude. However, HR, HRV, XRSA, and WCOH are either empirically related or more theoretically relevant than the other measures, and so receive the most interest here.

HR and respiration were also recorded during the experimental trials on a 0.5-s by 0.5-s basis. Respiration changes may be closely related to sustained attention (e.g., Porges, 1976), but they have been difficult to interpret in the context of the present research. I have chosen not to report on them in this chapter.

RESULTS

Study 1: Exploring a New Technique

The first study using the interrupted stimulus technique was designed to determine the feasibility of the technique for studying infant sustained attention (Richards, 1985b). I had found that the level of RSA in a baseline recording was significantly correlated with HR and visual responses during a visual habituation paradigm (Richards, 1985a). The greater the amplitude of RSA, the larger the HR response during fixation on the stimulus. Furthermore, the level of RSA was negatively correlated with visual fixation durations. Since fixation duration is known to decline with increases in age, this was taken to mean that the maturity of visual fixation duration was positively correlated with level of RSA. However, that study (Richards, 1985a) used the infant control procedure for stimulus duration, rather than the interrupted stimulus technique. As I have noted, the durations of visual fixation may be insufficient measures of visual attention.

Infants were presented checkerboard patterns for 12 trials in Study 1. The stimulus was presented on one half of the trials for as long as the infant was looking at it (infant control—IC trials). The other half of the trials consisted of the presentation of the central pattern for as long as the infant was looking, and the presentation of the interrupting stimulus in the periphery (interrupted stimulus—IS trials). The infant's gaze on each trial was directed to the central stimulus by a blinking light preceding the checkerboard pattern, insuring that the initial fixation was on the central stimulus.

The results of this study were very encouraging. First, for both the IC and IS trials, there was a large deceleration of HR immediately following fixation on the stimulus (Figure 1). This was true of the response for all three age groups. The HR patterns following the initial deceleration were of great interest. At 14 weeks of age, there was a gradual return towards the prestimulus level even though fixation was still occurring (Figure 1A). This was true for both IC and IS trials. There was a similar return of HR toward prestimulus levels in the IC trials of the 20- and 26-week olds, but not in the IS trials (Figure 1B, 1C). This was not due to different HR responses occurring on the two trials as a result of the interrupted stimulus in the periphery (see Study 2). Rather, it appears that when HR began to return toward prestimulus levels, fixation continued on the IC trials but was actively terminated on the IS trials. That is, there were periods of time in the IC trials when the HR response was finished, but the infant continued to fixate in the direction of the central stimulus. A conclusion that can be reached from this was that active processing of the stimulus occurred during the entire duration of the IS trials, but not during the entire duration of the IC trials.

How were the HR rhythms (RSA) related to responses in the two procedures? Baseline XRSA was positively correlated with the magnitude of the HR deceleration and negatively correlated with the length of fixation. The correlation between HR deceleration and XRSA was much stronger for the IS than the IC trials. This relationship of baseline XRSA with HR and visual fixation duration had already been shown in the earlier study with visual fixation habituation (Richards, 1985a). The nature of the relation between HR and XRSA was more closely examined by separating the HR response into short (less than 5 s) and long (greater than 5 s) latency responses. The level of RSA was uncorrelated with the short latency response in either of the procedures (Table 1A). It was, however, highly correlated with the long latency response, but only for the IS trials (Table 1B). Again, as in Richards (1985a), it was the measures of RSA, rather than overall HR variability, that were associated with the HR and visual fixation responses.

This study strongly supports the hypothesis that RSA predicts sustained attention ability in young infants. First, it is a reasonable assumption that the interrupted stimulus trials are indexing active processing of the stimulus. Second, it is the long latency portion of the HR response during active attention that is most highly correlated with the baseline RSA. Thus, it is the sustained attention system rather than the phasic OR that is related to level of RSA. A conclusion based on these findings is that "sustained attention capacity" is closely linked with ability to allocate processing resources to a visual attention task. Such an ability may be an "individual differences" psychological factor which can be measured with RSA.

Study 2: Can Active Processing Be Interrupted?

The results of Study 1 supported the theoretical link between sustained attention and baseline HR rhythms in young infants. However, some assumptions

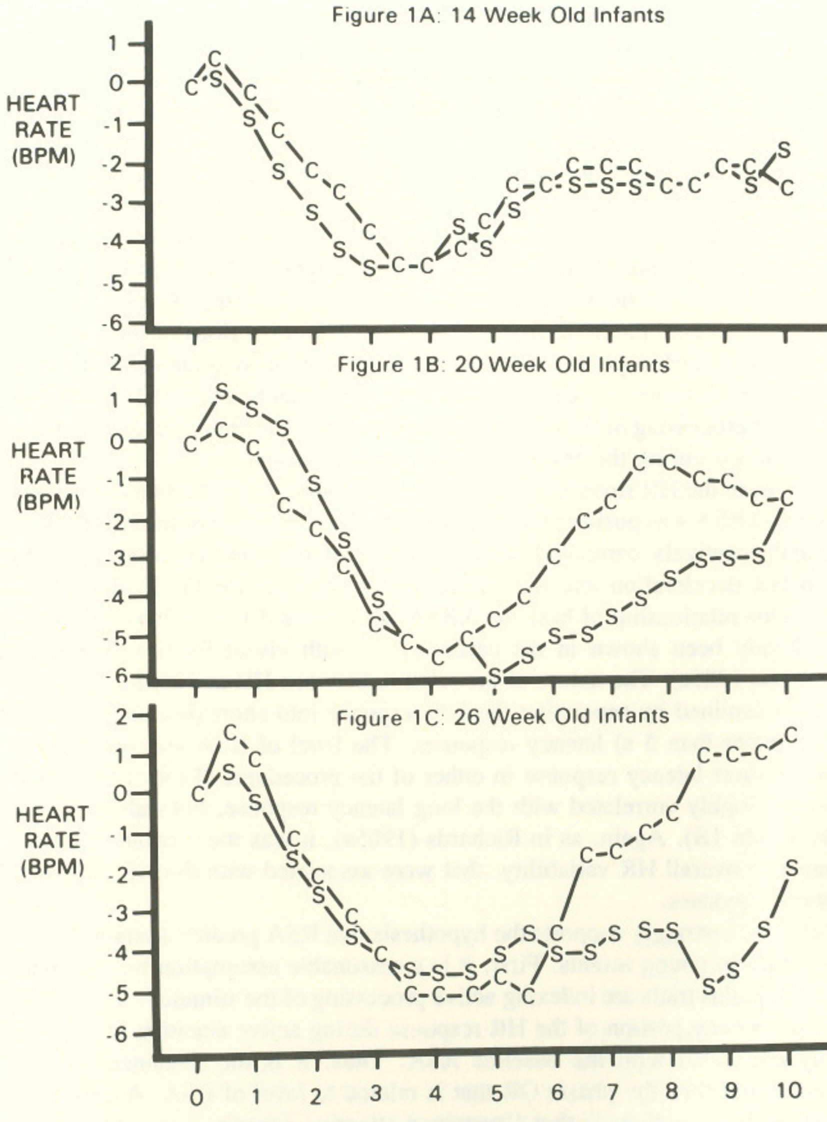

Figure 1. Average HR difference (bpm) between the fixation and prestimulus periods for 14-, 20-, and 26-week-old infants during the infant control (C) and interrupted stimulus (S) trials. The values are differences from the 5 s immediately preceeding the fixation. (From Richards, 1985b; used with permission.)

Table 1. Correlations between baseline heart rate variability and short and long latency heart rate responses for all subjects in the different experimental techniques (from Richards, 1985b; reprinted with permission).

Variable	*Infant Control*	*Interrupted Stimulus*	*Both Procedures*
A. *Short Latency Responses*			
BASELINE MEASURES			
Heart rate	−.09	−.04	−.09
Heart rate variance	−.19	−.08	−.18
Extent of sinus arrhythmia	−.10	−.03	−.09
Weighted coherence	.03	−.06	−.02
B. *Long Latency Responses*			
BASELINE MEASURES			
Heart rate	−.10	−.01	−.06
Heart rate variance	−.29**	−.19	−.29**
Extent of sinus arrhythmia	−.12	−.43**	−.35**
Weighted coherence	−.10	−.28*	−.24*

*$p < .05$
**$p < .01$

made about HR responses in that study may be unwarranted. One such assumption is that the sustained, long latency HR slowing on the interrupted stimulus trials was evidence that cognitive processing was still occurring. This may be an unreasonable assumption, since not much is known about the HR response that actually occurs during sustained attention in infants. It may be that the return of HR to prestimulus levels in the youngest infants, and during the infant control trials, is not linked to the cessation of active cognitive processing. For these reasons, it seemed necessary to show a relation between focusing of attention on the central stimulus (avoiding distraction) and concurrent HR level decrease. The infant should be more distractable when HR returns to prestimulus levels than when it is still far below prestimulus levels.

A second assumption of Study 1 concerns the nature of the attentional activity in the short and long latency intervals. According to the model of attention activity presented in this chapter (cf. Porges, 1976), the first few seconds following a stimulus are associated with "phasic" attention, while the subsequent seconds are associated with "sustained" attention. The HR response data, as well as the significant correlations between RSA and the long latency HR response, were interpreted as support for this model of sustained attention. However, the interrupting stimulus was on during the entire presentation of the primary stimulus. It would be important to determine if the attention activity could be interrupted at the time the presumed attention process is occurring. Thus, the presentation of the secondary task should be delayed to correspond to the phase of attention.

The second study was designed to answer these questions. Infants at the different ages were presented with patterned visual stimuli. These patterns were found in pilot testing to elicit long periods of fixation, and in this sense were superior to the checkerboard patterns used in Study 1. The assumption that continued HR suppression accompanies sustained cognitive processing was tested. The interrupting stimulus was presented during some trials when the HR response was at its maximum (HRDEC trials), and during others when the HR level began to return to the prestimulus levels (HRACC trials). The infant should be less distractable during the HRDEC than during the HRACC trials if HR deceleration is coincident with cognitive processing. The interrupting stimulus was also presented at delays of three (3SEC trials) or seven seconds (7SEC trials) following fixation, to test the idea that the phases of attention (OR/sustained) follow a regular time course. The infant control procedure (IC trials) was also used for comparison.

The manipulation for the HRDEC and the HRACC trials was successful. Figure 2 shows the HR change from the prestimulus period for the 2.5 s preceding the onset of the interrupting stimulus, and from the 2.5 s following its onset but before the infant looked towards it. As defined by the protocols, HR on the HRDEC trials was decelerating from the prestimulus level when the interrupting stimulus was turned on. HR on the HRACC trials was accelerating towards the prestimulus level when the IS was turned on. The mean time to notice the interrupting stimulus was 6.67 s on the HRDEC trials, much longer than the 3.29 s mean distraction time on the HRACC trials. Thus, when the infants were looking at the central stimulus and actively attending to it (HRDEC trials), it took longer to be distracted than when they were looking at the central stimulus and not paying attention to it (HRACC trials). This is direct experimental evidence that HR lowering is coincident with ''focusing'' of attention in this paradigm.

The HR and fixation responses on the 3SEC and 7SEC trials are also relevant to the question of the HR-attention relationship. A limitation of the HRDEC/HRACC manipulation was that the interrupting stimulus began much later for the HRACC trials (10.23 s) than for the HRDEC trials (3.61 s). It could be that the longer distraction time on the HRDEC trials was merely a result of the stimulus' being presented earlier, and a fixed duration of focused attention occurred in both conditions. This limitation can be partially answered by looking at HR level at the same point in time (3s or 7s), and determining the distraction time given that HR level. The 3SEC and 7SEC trials were divided based on the HR response during the 2.5 s following the onset of the interrupting stimulus, but before the infant had been distracted by it. The time necessary for the distraction was the longest (6.52 and 5.48 s for the 3SEC and 7SEC trials, respectively) on the trials when the HR level was at or below the mean level of the HRDEC trials, and therefore still decelerating below the prestim-

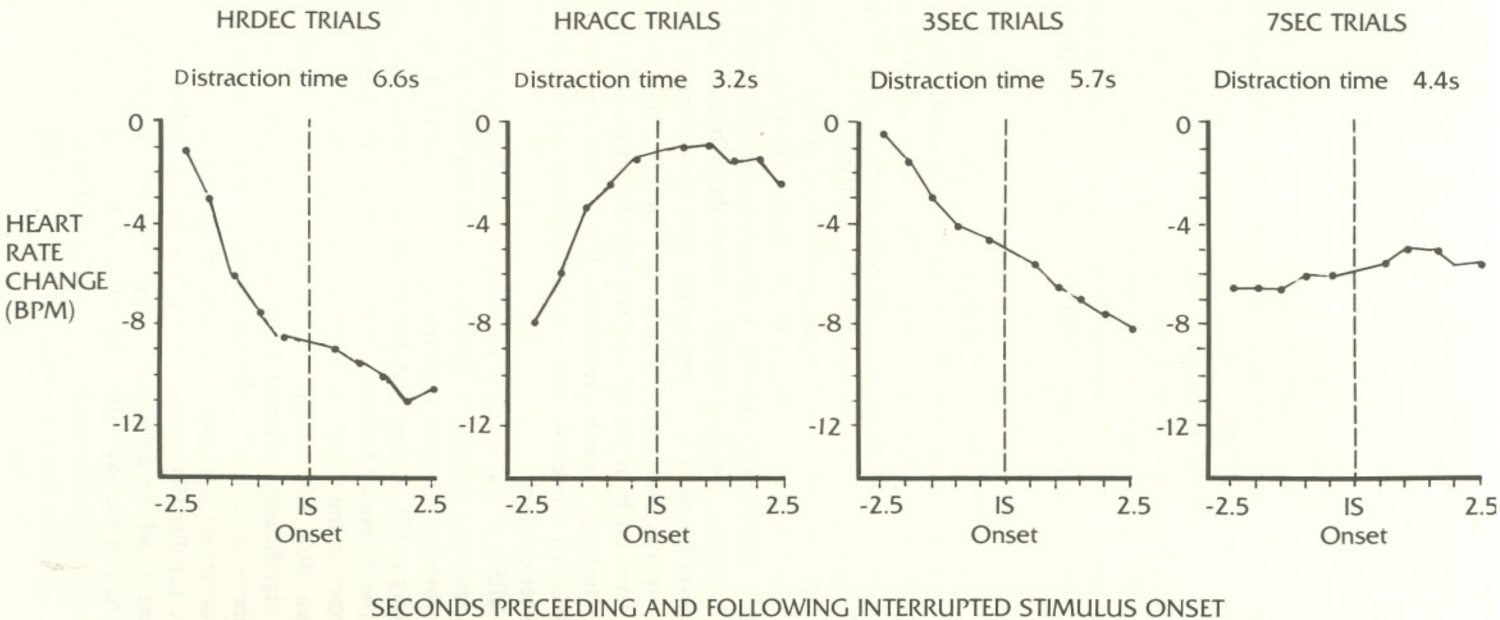

Figure 2. Average HR difference (bpm) between the prestimulus 2.5 s average, and for 2.5 s immediately preceding and following the onset of the interrupting stimulus for the procedures of Study 2. The average distraction time for each procedure is also presented.

ulus level. The distraction time on the 3SEC and 7SEC trials was the shortest (4.77 and 4.07 s, respectively) when the HR level was at or above the mean level of the HRACC trials. Thus, when time is experimentally controlled, the level of HR covaries with the amount of time it takes to distract the infant from the primary task. The mean distraction times for the trials divided this way were not different for the 3SEC and 7SEC trials. This is contrary to what might be expected if there were a rigorous time course of phasic (0 to 5 s) and sustained (5 plus seconds) attention measured by these two procedures. Another relevant finding was that the mean time to distract the infant is ordered for the four procedures in the same way as the direction in which HR is changing at the time the interrupting stimulus is presented (HRDEC, 3SEC, 7SEC, HRACC; see Figure 2).

A comparison between the interrupted stimulus procedures (HRDEC, HRACC, 3SEC, and 7SEC) and the IC trials can also be made. The fixation duration on the IC trials was close to the overall fixation duration only on the HRACC trials (12.82 and 13.52 s, respectively). The other interrupted stimulus procedures resulted in trial durations of significantly shorter duration. This suggests that the IC trials were similar in nature to the HRACC trials. In other words, infants continue to look at a stimulus for some period of time after active attention has finished, if uninterrupted by another stimulus or task. This similarity is further supported by the HR responses immediately prior to looking away from the central stimulus. Figure 3 shows the difference in HR from the prestimulus level for the 2.5 s immediately prior to the time at which the infants looked away from the central stimulus, and for 5.0s after having looked away. The HR level on both the IC and the HRACC trials had already returned, or was returning, towards prestimulus levels when the infant looked away. This implies that active attention was terminated in the IC trials 1 to 2 s prior to fixation termination.

The level of XRSA in the baseline period was significantly related to the infant's HR responses and distraction times only for the HRDEC trials. This was examined by performing a median split on the level of XRSA in the baseline period, and looking at HR changes and distraction times for the low- and high-XRSA infants. The difference between the high- and low-XRSA groups on HR change and distraction time was not significant for the HRACC, 3SEC, and 7SEC procedures. Both HR change and distraction times with the HRDEC procedure were significantly different for these two groups. The level of the deceleration immediately following the interrupting stimulus onset (but before distraction had occurred) was larger in the high-XRSA infants (-11.39 bpm change from prestimulus level) than for the low-XRSA infants (-7.72 bpm change). The time it took for distraction to occur was longer in the high-XRSA infants (7.73s) than in the low-XRSA infants (5.40s). Thus, the low-XRSA infants were more easily distractable from the central task, and had less HR deceleration during active attention, than did the high-XRSA infants. On the

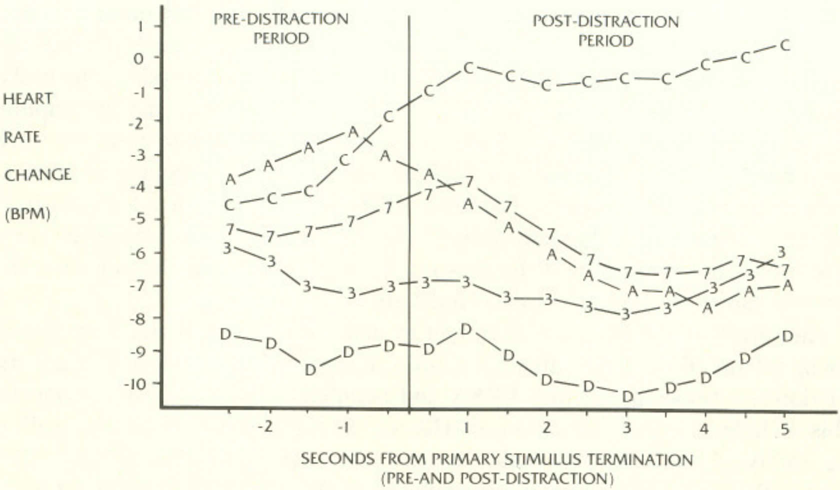

Figure 3. Average HR difference (bpm) between the prestimulus 2.5 s average, and for 2.5 s preceding and 5 s following the infant's looking away from the primary stimulus. The procedures were HRDEC (D), HRACC (A), 3SEC (3), 7SEC (7), and IC (C).

other hand, there was a tendency ($p = .073$) for the high-XRSA infants to look for shorter periods than the low-XRSA infants on the HRACC, 3SEC, 7SEC, and IC trials (13.76 & 13.3s; 9.19 & 8.7s; 11.65 & 11.59s; 13.94 & 11.59s, respectively).

The relationship of XRSA and HR changes is consistent with that found in Study 1. However, the *positive* correlation between distraction time and XRSA on the HRDEC trials in this study was different from the *negative* correlation between XRSA and distraction time in Study 1. The negative correlation had been interpreted as showing that more mature infants, who show shorter fixation durations, were also those with higher levels of XRSA (Richards, 1985a, 1985b). However, a different interpretation must be considered that integrates those results with the results of the present study. The high-XRSA infants may respond more quickly than the low-XRSA infants, particularly to terminate fixation, when attention is not strongly aroused. This is partially supported by the shorter time for the high-XRSA infants to meet the HRACC criterion (9.74s) compared to the low-XRSA infants (10.77s). It is also supported by the difference in distraction times on the trials other than the HRDEC trials: high-XRSA infants had shorter distraction times than the low-XRSA infants. Thus, when attention is fully engaged, the high-XRSA infants do much better at focused, undistractable attention, and the low-XRSA infants do more poorly. When attention is not fully engaged, the high-XRSA infants react more quickly than the low-XRSA infants.

There were few age differences in the present study. The HR onset response was the same for the 14-, 20-, and 26-week-old infants. Furthermore, the HR responses of the age groups were not different for the other periods in the trials. Overall fixation duration, as well as the time it took to notice the interrupting stimulus, decreased with age. Figure 4 shows the distraction time for each interrupted stimulus procedure, for each of the three ages. A regular decrease in distraction time can be seen for HRDEC, HRACC, 3SEC, and to a lesser degree, the 7SEC procedures. The generality of this effect over all the interrupted stimulus procedures implies that the reasons for the decrease in fixation time are general, rather than specific to sustained attention.

The results of Study 2 are important in understanding sustained attention in young infants. First, when attention is fully engaged, as in the HRDEC trials, the relationship between baseline XRSA and attention responses is the strongest. This includes larger decelerations of HR for the high-XRSA infants, as well as the ability to withstand distraction by the interrupting stimulus. On the other hand, XRSA does not discriminate the characteristics of HR or distraction time at the end of active attention (HRACC trials). Thus XRSA is related to sustained attention activity while it is in progress, but not necessarily to reactivity to new stimuli at the end of attention (HRACC trials) or at the beginning of attention (the HR OR). There is a decrease in fixation time, as well as a decrease in the time it takes to be distracted by the interrupting stimulus, over the age range used in this study. However, this appears to be a general decrease in fixation duration, rather than one specifically involving active attention processes.

Study 3: Heart Rate Changes at Attention Termination

One of the aims in using the interrupted stimulus procedure is that it provides a method of assessing the voluntary allocation of attention by the infant rather than passive (or obligatory) attention processes. One characteristic of voluntary attention is also voluntary termination of fixation, highlighted procedurally by use of the control of stimulus duration based on infant fixation (cf. Cohen, 1972; Horowitz et al., 1972). The HR offset response may be relevant in this regard. One characteristic of the OR is that there should be an HR response to the offset of a stimulus (Graham & Clifton, 1966; Sokolov, 1963). The development of the offset response to auditory stimuli has been studied in young infants in several studies (e.g., Berg, 1972, 1974; Lewis, 1971). A brief (1 to 3 s) and small magnitude (1 to 5 bpm) HR deceleration occurred at the end of an auditory stimulus which was presented for a fixed period of time. There is little developmental change in the offset response, particularly for the first six months of life. The existence of the offset response in young infants implies that phasic attention responses (e.g., an OR) are engaged at the forced termination of stimulation.

The studies of stimulus offset do not provide much information about *infant-initiated* termination of visual attention. However, to date, experiments have

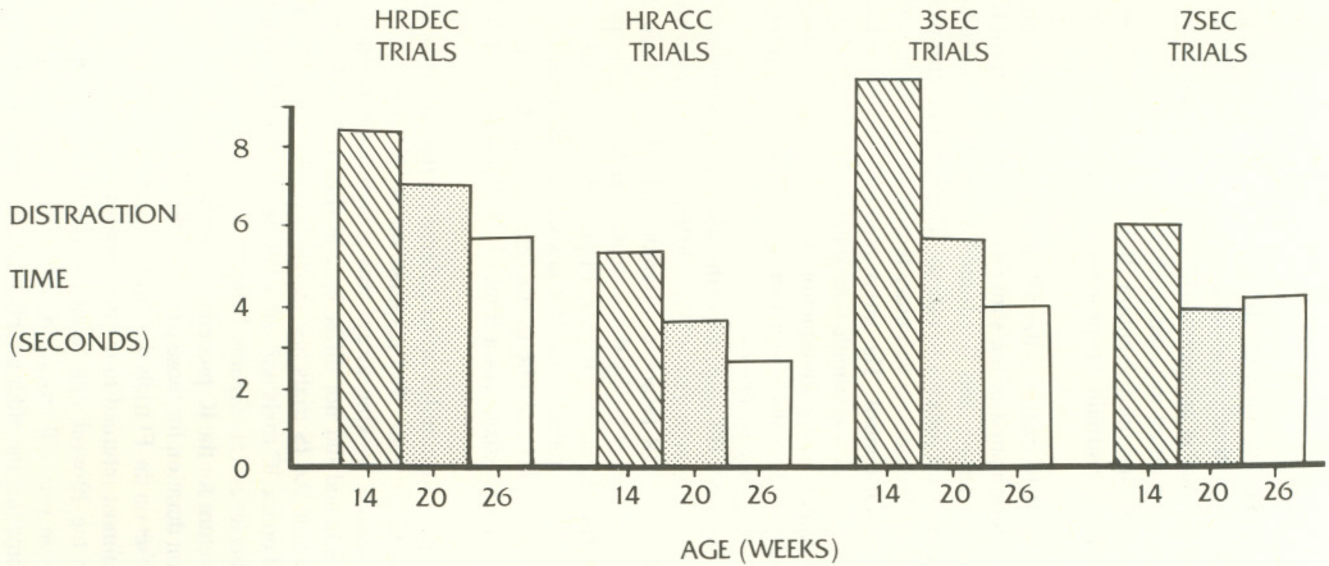

Figure 4. Average distraction time for the 14-, 20-, and 26-week olds, for the interrupted stimulus procedures of Study 2.

presented the stimulus for a fixed interval of time without regard for what the infant was actually doing. For auditory stimuli, the experimenter assumes that the obligatory nature of the stimulus means that the infant will notice its termination. This type of procedure is an *experimenter-initiated* stimulus termination. As such, it cannot reflect infant-initiated control and thus does not reflect the termination of voluntary, sustained attention. It cannot answer the questions of why infants will voluntarily sustain attention to a stimulus, nor why they decide to stop looking.

Study 3 was designed to examine the offset responses of the infant using voluntary and forced termination of the stimulus. The infant control (IC trials), interrupted stimulus (IS trials), and fixed-interval (FI trials) procedures were used to present checkerboard patterns to infants. The infant control procedure is fully infant-initiated, and represents voluntary termination of the stimulus which is not under experimental control. The interrupted stimulus procedure reflects infant-initiated termination of the stimulus presentation, which has been brought under experimental control by the introduction of the interrupting stimulus. The fixed-interval procedure represents a forced termination of the stimulus, independent of the infant's voluntary processes.

As with Study 1, the onset HR response to the stimulus presentation in Study 3 was a 5 to 6 bpm HR deceleration that was not different for the three testing ages (see Figure 1). The offset HR response differed markedly for these three procedures. Figure 5 shows the 0.5-s by 0.5-s changes in HR for 5 s prior to and following stimulus offset for the IS, IC, and FI procedures. The HR response to the offset of the primary stimulus on the IS trials was a large HR deceleration as would be expected since it is an OR to the interrupting stimulus. The offset response for the FI and IC trials was a brief (2–3 s) and small (1.5 bpm) HR deceleration.

The HR response prior to stimulus offset differed for the three procedures, and differed by age for the FI trials. The response on the IC and IS trials prior to stimulus offset (voluntary looking away) was a significant return toward the prestimulus HR level, and did not differ by age (Figure 5). However, visual termination occurred on the IS trials just as HR began to return to prestimulus levels, but occurred on the IC trials only after HR had completely returned to and exceeded prestimulus levels (cf. Figures 3 and 5). Thus, there was about 1 to 1.5 s of additional HR return for the IC procedure, which likely reflects the 1 to 1.5 s of additional fixation duration for those trials. On the other hand, the HR pattern prior to stimulus offset on the FI trials did differ for the three ages. The HR of the 26-week olds had almost returned to the prestimulus level prior to the stimulus termination, that of the 20-week olds to an intermediate level, and the 14-week olds' HR deceleration was still sustained. This result was probably due to the shorter periods of time that the older infants fixated on the stimulus. The 26- and 20-week olds were nearly ready to initiate voluntary stimulus termination when the stimulus was experimentally terminated.

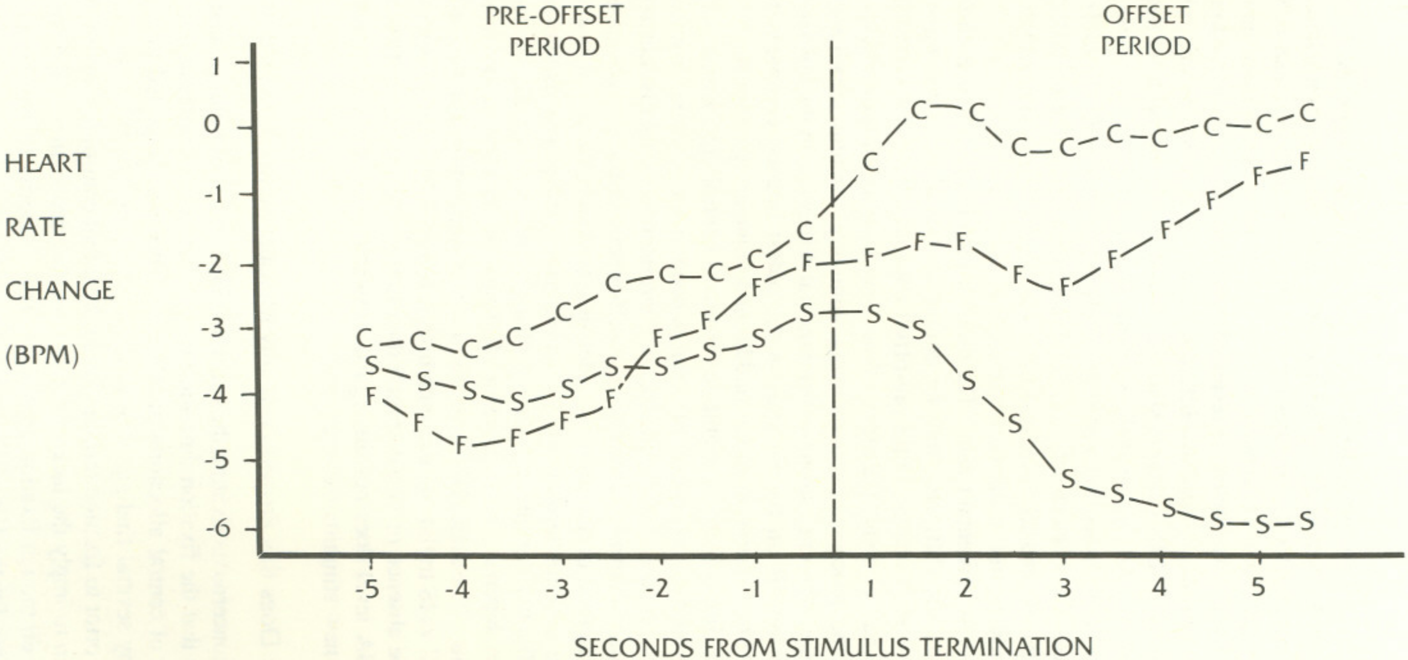

Figure 5. Average HR difference (bpm) between the prestimulus 2.5 s average, and for 5 s preceding and following the primary stimulus offset. The procedures were the fixed interval (F), infant control (C), and interrupted stimulus (S).

The level of RSA in the baseline was related to the strength of the offset responses. This was examined by a median split within each age on XRSA, and by using that as a factor for separating 0.5-s by 0.5-s HR response patterns. There was no significant difference in the onset HR response for high- and low-XRSA infants. Similarly, the offset response in the IS procedure, really an OR to the interrupting stimulus, was not differentiated by the XRSA groups. On the other hand, the high-XRSA infants showed a larger offset response on both the FI and IC trials than did the low-XRSA infants (Figure 6). This effect was more pronounced on the IC trials, but was statistically significant on the FI trials also. There were also some effects of the XRSA median split on the pre-offset HR responses on the IC and IS trials which lead to some of the same conclusions reached in Study 1, and so are not reported here.

Were there developmental trends? The time of the initiation of fixation for the IC and IS trials was different, and the duration of fixation for the three ages differed. However, the nature of the pre-offset HR return was identical on the IC and IS trials. Thus, although the older infants were looking for shorter durations, the nature of the processes accompanying voluntary stimulus termination remained the same. The only strong developmental difference in the HR response was the return of HR on the FI trials in the oldest infants, compared to the sustaining of HR deceleration in the middle and younger age groups.

These results imply that the cognitive processes controlling fixation termination and the voluntary control of attention depend on the context in which the visual attention occurs. When the fixation termination is totally outside the infant's voluntary control (FI trials), age differences result that are based on the faster termination of attention for older infants. When the infant is actively involved in the attention termination (IC and IS trials), the processes immediately preceding fixation termination do not change with age, but the subsequent offset response depends on the presence (IS trials) or the absence (IC trials) of other stimulation. The offset HR response to visual stimulation is not identical to the HR OR (IC vs IS trials). Infants with high levels of RSA show a larger offset response in the absence of visual stimuli than those with low levels (IC and FI trials), but RSA level does not distinguish between "offset" responses in the presence of a new stimulus (IS trials).

Study 4: Does this Procedure Really Measure Active Processing?

One of the concerns motivating the use of the interrupted stimulus procedure is the possibility that the fixation duration in the infant control procedure is not a good measure of central allocation of attention. This was suggested in the first three studies by several findings. For example, the return of HR towards prestimulus levels prior to fixation termination in the infant control procedure (Study 2, 3) was taken to imply the lack of active cognitive processing of the stimulus information even though fixation continued. The similarity of the pre-termination HR response for the HRACC and IC trials in Study 2 is most important in

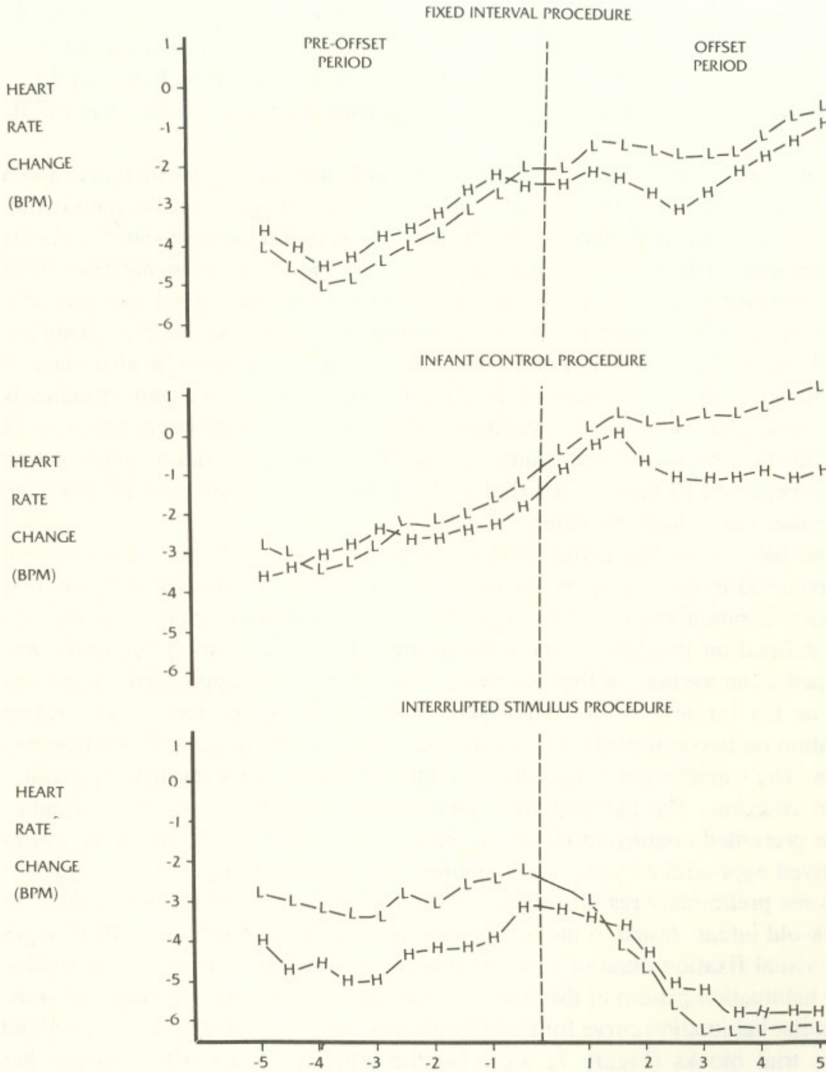

Figure 6. Average HR difference (bpm) between the prestimulus 2.5 s average, and for 5 s preceding and following the primary stimulus offset for the low- (L) and high- (H) XRSA subjects.

this regard. There are at least two implications of this interpretation of the IC/IS trials difference. First, if only active processing is allowed on IS trials, and IC trials consist of active processing followed by "blank stare" time, then the information in the stimulus should be processed more effectively with the same amount of time on IS than on IC trials. Secondly, if RSA level is related to sustained attention capacity, or to the quality of information processing, then the high-RSA infants should do better in the same amount of time processing the information contained in the stimulus. This difference should be larger on the IS trials since they are presumed to measure sustained attention better than the IC trials.

How can this be tested? A type of task which measures infant memory, and a criterion which may assess the interrupted stimulus procedure, is the habituation task. Habituation is defined as the decline in a response with repeated stimulus presentation. HR responses and visual fixation duration show habituation to checkerboard patterns (e.g., Richards, 1985a). If the interrupted stimulus procedure is measuring attention, then the duration of fixation on the IS trials should regularly decline with repeated presentation. The infant should also show a significant response recovery of HR and fixation time when a new stimulus is presented. Additionally, if sustained HR lowering indicates the presence of sustained cognitive activity (Study 2), then HR responses should parallel fixation times better on IS than on IC trials if the former is measuring central attention processes better than the latter.

The habituation procedure for Study 4 was as follows. IS and IC trials were interspersed in equal proportions throughout the habituation sequence. The first fixation duration and the criterion trials were defined on IC trials for one group and defined on IS trials for the other group. The ''first fixation duration'' was defined as an average of the first two presentations of the appropriate procedure (IC or IS) for that group. The habituation criterion was defined as fixation duration on two consecutive trials equaling one-half the fixation of the first two trials. The stimuli were repeatedly presented until the infants reached this habituation criterion. The habituation sequence and the response recovery stimulus were presented contingent either on the IC or on the IS trials, but both groups received approximately the same number of IC and IS trials.

Some preliminary results of these two procedures are available for twelve 26-week-old infants tested in the two conditions. Figure 7 presents the HR changes and visual fixation durations for the phases of habituation in three-trial blocks. The habituation pattern of the visual fixation duration and the HR response show a similar habituation curve for the IS trials, declining to near-zero levels by about three trial blocks (Figure 7, top). On the other hand, the HR response has habituated by about the third trial block for the IC procedure group, but visual fixation continues on the fourth, fifth, and even sixth trial blocks (Figure 7, bottom). Thus, according to fixation duration on the IC trials, the infant still has not habituated, whereas according to the HR response, the infant has habituated. The fixation durations and the HR responses on the response recovery trials were not significantly different for the two procedures. The similar habituation pattern of visual fixation and HR deceleration on the IS trials supports the notion that the fixation duration on those trials is a better behavioral measure of active cognitive processing than is fixation duration on the IC trials.

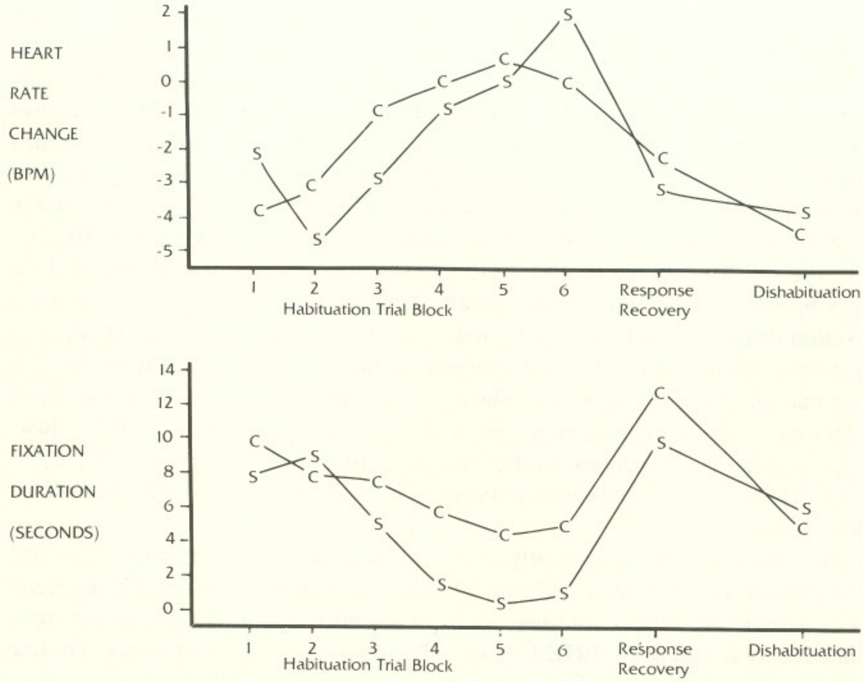

Figure 7. The average HR change (bpm) between the prestimulus and fixation periods for the phases of habituation, and the average fixation duration for the same habituation phases.

INFANT VISUAL SUSTAINED ATTENTION

The studies reported in this chapter shed light on the psychophysiology of infant visual sustained attention. Sustained attention may be characterized as voluntary, subject-initiated, and subject-sustained active processing of stimulus information. The interrupted stimulus methodology is a measure of sustained attention, since it measures the amount of processing resources allocated to a visual stimulus. The infant is not distractable from attention to the stimulus when the HR response is at its maximal level. The results of the infant control procedure show that infants will continue to fixate on a central stimulus even though central attention processes have diminished (or ceased). The infant is highly distractable from the central task when HR returns to its prestimulus level, indicating that central allocation of processing resources (i.e., sustained attention) has ceased.

The question of developmental changes in sustained attention over the period from three to six months of age is not so clearly answered by these studies. The most consistent finding over all of the studies is a decrease in average fixation duration from 14 to 26 weeks of age. Originally, I had interpreted this to indicate a superior processing ability of the older infants compared with the younger infants (Richards, 1985a, 1985b). This was partially based on the return of HR towards baseline levels in the 14-week-olds in both the IC and IS procedures (Study 1). If this developmental difference applied specifically to sustained attention, one would expect it to show up most strongly in the HRDEC trials of Study 2, and not in the HRACC nor in the IC trials. This developmental trend in shorter fixation times was found in all procedures in Study 2. Voluntary fixation termination, for both the IC and the IS trials in Study 3, was preceded in all three ages by HR return to prestimulus levels. Thus, though the overall length of the fixation decreases over this age period, it does not decrease through changes in sustained attention nor through changes in the processes controlling fixation termination. Other studies have shown that older infants process information faster than younger infants (e.g., Rose, 1983; Zelazo & Kearsley, 1982). However, if there is an increase in the "quality" of information processing, it has been detected neither psychophysiologically nor behaviorally in the present series of studies.

The extent of RSA was closely related to sustained attention ability. The first two studies showed that XRSA was closely related to the level of HR deceleration, particularly in the sustained phase of attention (Study 1) and during maximal attention (Study 2, HRDEC trials). The relation of RSA to fixation duration is not as straightforward. For the most part, it appears that XRSA is inversely related to fixation duration. Shorter fixation durations have been interpreted as indicating a more mature fixation level (Richards, 1985a, 1985b), but this may not necessarily be true. This is demonstrated by the relative indistractibility of the high-XRSA infants in the HRDEC trials of Study 2. One interpretation of these results is that the high-XRSA infants do well at focusing their attention and are not distractible when attention is fully engaged, but are more reactive than low-XRSA infants when attention is partially engaged. Further study will be necessary to evaluate the possibilities. The relationship of RSA to other aspects of infant behavior, such as developmental level (Fox & Porges, 1985) and infant memory ability (Linnemeyer & Porges, 1986), may be based on the correlation between high quality attention processes and XRSA.

Is the interrupted stimulus method better than the infant control method for measuring attention in infants? Yes, and no. It is a better measure in several ways. It brings the termination of fixation under experimental control without the domination of the termination process by the experimenter. The interrupted stimulus procedure eliminates the periods of time during infant fixation when the infant may be fixating on the stimulus but not actually engaging in cognitive processing of stimulus information. This was shown by the similarity of the HRACC and IC trials in Study 2, the return of HR to prestimulus levels prior to fixation termination in Study 3, and the closer relationship of fixation habituation to HR habituation in Study 4. The RSA/HR-change relationship was the strongest in Study 1 and Study 2 for the interrupted stimulus procedure trials. These considerations suggest that the interrupted stimulus method is superior to the infant control method for measuring sustained attention. Future study of this question may revolve around the actual performance on information processing tasks (such as a memory task) based on the two procedures. On the other hand, often in the infant's environment the context of stimulus termination more closely matches the infant control or the fixed-interval procedures. Thus, these procedures remain useful tools for the study of infant visual attention.

One area of inquiry for future study of sustained attention in infants is the analysis of other physiological systems in the interrupted stimulus procedure. According to adult research and research with older children, sustained attention is accompanied by changes in HR, HR variability, respiration frequency and amplitude, and respiratory variability (e.g., Coles, 1982; Porges & Raskin, 1969; Porges & Humphrey, 1977). Do these same things happen during infant visual sustained attention? Research of this nature would characterize the pattern of psychophysiological responses associated with sustained attention over several response systems. Other physiological systems (e.g., blink reflex, pupil dilations, etc.), which are psychophysiological concomitants of attentional processes, may also be profitable for the study of infant visual sustained attention. This type of research could use the confirmatory multivariate models of linear structural equations modeling, since specific hypotheses exist which relate the pattern of baseline cardiac rhythms to behavioral and psychophysiological patterns during the phases of attention (e.g., Richards & Turner, 1984). The interrelationship among the different physiological systems may also be used to address the question of whether RSA predicts attentional responsivity because it is an estimate of vagal tone, or because it is a measure of general brainstem functional integrity. Physiological systems under brainstem control but not influenced by the parasympathetic nervous system could be used to tease out the relative contributions of the vagal and brainstem systems to sustained attention.

Another improvement that could be made in the study of infant sustained attention is in the nature of the tasks in which the infant engages. Tasks exist for adults and older children in which quality of task performance can be evaluated. This is especially true of dual-processing procedures, in which the measure of resource allocation to the primary task is the degradation of performance level (more errors, slower, etc.) on the secondary task. Actual measures of infant performance (and errors) on cognitive tasks are very rare, with perhaps the only exception being the memory task devised by Fagan (e.g., Fagan & McGrath, 1981). That task, however, is not useful for a wide variety of cognitive tasks. The tasks in the present study involve passive viewing of visual stimuli, with the duration of fixation before distraction as the primary measure of active processing. Other areas of infant research would also be improved by the development of tasks which measure actual performance. I expect that on such tasks, the performance in dual-processing paradigms will be more strongly related to RSA and show greater developmental differences than on the tasks used in the present studies.

Complicating factors in the study of the relationship between RSA and sustained attention are the developmental, pathological, and individual differences factors that may affect the relationship. The effects of these three domains on the RSA-attention relationship are parallel. Table 2 contains some characteristics of good and poor patterns of sustained attention. There are developmental changes in HR and respiration in the first few months of infancy which parallel the presumed individual differences in sustained attention. There are decreases in HR (Harper et al., 1976), respiration rate, and respiration rate variability (Hoppenbrouwers et al., 1978). Overall HR variability increases over the early months of infancy (Harper et al., 1976; Katona, Frasz, & Egbert, 1980; Watanabe, Iwase, & Hara, 1973), and there are also increases in HR variability specifically due to RSA (Katona et al., 1980; Harper et al., 1978). The possibility exists that the relationship between the physiological and attentional systems is caused by developmental changes in both. Thus an important question is whether the individual differences in sustained attention predicted by RSA are stable across these ages irrespective of the age differences in the RSA and

Table 2. Developmental, pathological, and individual differences in sustained attention: A comparison.

Quality of Attention	
"Poor" Attention	*"Good" Attention*
A. Characteristics of the differences	
Low RSA	High RSA
Small HR changes during attention	Large HR changes during attention
Long fixation duration, but,	Short fixation duration, but,
Easily distracted when paying attention	Not easily distracted when central processes engaged
Slow cognitive processing	Fast cognitive processing
Equal cognitive abilities when other things held equal	
B. Domains of the differences	
Developmental	
Young infants	Older infants
Pathological	
Pathological groups	Normal infants
Individual	
Below the norm	At or above the norm

attentional systems. As pointed out by developmental theorists (e.g., McCall, 1977; Wohlwill, 1973), this type of question can only be answered by longitudinal studies.

Another area of individual differences related to RSA is behavioral temperament. Kagan and his colleagues have established a link between "behaviorally inhibited" children and low levels of HR variability (Garcia-Coll, Kagan, & Reznick, 1984; Kagan, 1982; Kagan, Kersley, & Zelazo, 1978; Kagan et al., 1984). Children who are behaviorally inhibited are reticent in engaging in activity in unfamiliar situations, and approach them with extreme caution. Behaviorally inhibited children show lower levels of HR variability during resting conditions—as well as during attention or stressful situations—than do behaviorally uninhibited children. Kagan proposes that the relationship between HR variability and behavioral inhibition is due to the dominance of the sympathetic, rather than the parasympathetic, branch of the autonomic nervous system in the inhibited children. Nonetheless, the relationship between behavioral inhibition and HR variability may be partially based on differing patterns of sustained attention, so that an overlap between the RSA-inhibition and RSA-sustained attention relations would be found. This type of relationship would suggest a strong stability of individual differences, as well as a provocative inter-domain relationship.

A very important application of this research concerns the immature patterns of attention found in pathological populations. The individual differences in the RSA-attention relationship are paralleled by pathological differences as well as by developmental differences (Table 2). Porges (1976, 1980) argues that populations such as hyperactive or mentally retarded children show deficiencies in attention which may be related to their level of RSA. For example, respiration and HR responses during visual attention in mentally retarded children are unrelated, whereas they are coincident in normal children (Porges & Humphrey, 1977). It has also been shown that methylphenidate (Ritalin) given to hyperactive children results in (a) an increase in RSA in resting periods (Porges et al., 1981), and (b) increases in both fixation duration and cardiac responses which are more typical of the mature pattern of adult attentional responses (Porges, Walter, Korb, & Sprague, 1975). The implication of these studies is that the RSA level assesses the CNS mechanism(s) which is responsible for the immature attentional response. Furthermore, this research implies that the study of individual differences in attentional responsivity may be useful for understanding and alleviating pathological attentional responses. Currently, we are trying to unravel the developmental, individual, and pathological differences with a longitudinal study of infants who are "at-risk" for attentional disabilities in childhood, and who also show immature levels of RSA and immature attentional patterns in infancy. Thus, infant sustained attention may provide a "model preparation" for the study of the problems of older children's attention, as well as being useful for the direct study of infants with attentional disabilities.

ACKNOWLEDGMENTS

Part of this work was supported by a New Investigator Research Award #1 R23 HD18942-01A1, from the National Institute of Child Health and Human Development.

REFERENCES

Adkinson, C. D., & Berg, W. K. (1976). Cardiac deceleration in newborns: Habituation, dishabituation, and offset responses. *Psychophysiology, 21,* 46–60.

Anrep, G. W., Pascual, W., & Rossler, R. (1935). Respiratory variations of the heart rate. I. The reflex mechanism of the respiratory arrhythmia. *Royal Society of London Proceedings, Series B, 119,* 191–217.

Anthony, B. J., & Graham, F. K. (1983). Evidence for sensory-selective set in young infants. *Science, 220,* 742–744.

Appel, M. A., & Campos, J. J. (1977). Binocular disparity as a discriminable stimulus parameter for young infants. *Journal of Experimental Child Psychology, 23,* 47–56.

Baker, T. L., & McGinty, D. J. (1977). Reversal of cardiopulmonary failure during active sleep in hypoxic kittens: Implications for Sudden Infant Death. *Science, 198,* 419–421.

Baker, T. L., & McGinty, D. J. (1978). Sleep apnea in hypoxic and normal kittens. *Developmental Psychobiology, 12,* 577–594.

Berg, W. K. (1972). Habituation and dishabituation of cardiac responses in 4-month-old, alert infants. *Journal of Experimental Child Psychology, 14,* 92–107.

Berg, W. K. (1974). Cardiac orienting responses of 6- and 16-week-old infants. *Journal of Experimental Child Psychology, 17,* 303–312.

Berg, W. K. (1975). Cardiac components of defense response in infants. *Psychophysiology, 12,* 224.

Berg, W. K., & Berg, K. M. (1979). Psychophysiological development in infancy: State, sensory function, and attention. In J. Osofsky (Ed.), *Handbook of infant development* (pp. 283–343). New York: J. Wiley.

Bohrer, R. E., & Porges, S. W. (1982). The application of time-series statistics to psychological research: An introduction. In G. Kesen (Ed.), *Statistical and methodological issues in psychology and social science research* (pp. 309–345). Hillsdale, NJ: Erlbaum.

Broadbent, D. E. (1958). *Perception and communication.* New York: Pergamon Press.

Brooks, P. R., & Berg, W. K. (1979). Do 16-week-old infants anticipate stimulus offsets? *Developmental Psychobiology, 12,* 329–334.

Campos, J. J., Emde, R., Gaensbauer, T., & Henderson, C. (1975). Cardiac and behavioral interrelationships in the reactions of infants to strangers. *Developmental Psychology, 11,* 589–601.

Campos, J. J., Langer, A., & Krowitz, A. (1970). Cardiac response on the visual cliff in prelocomotor human infants. *Science, 170,* 196–197.

Clarkson, M. G., & Berg, W. K. (1983). Cardiac orienting and vowel discrimination in newborns: Crucial stimulus parameters. *Child Development, 54,* 162–171.

Cohen, L. B. (1972). Attention-getting and attention-holding processes of infant visual preferences. *Child Development, 43,* 869–879.

Coles, M. G. H. (1972). Cardiac and respiratory activity during visual search. *Journal of Experimental Psychology, 96,* 371–379.

Dawson, M. E., Schell, A. M., Beers, J. R., & Kelly, A. (1982). Allocation of cognitive processing during human autonomic classical conditioning. *Journal of Experimental Psychology: General, 111,* 273–295.

Egbert, J. R., & Katona, P. G. (1980). Development of autonomic heart rate control in the kitten during sleep. *American Journal of Physiology, 238,* H829–H835.

Fagan, J. F., & McGrath, S. K. (1981). Infant recognition memory and later intelligence. *Intelligence, 5,* 351–356.

Fantz, R. L. (1963). Pattern vision in newborn infants. *Science, 140,* 296–297.

Fox, N. A., & Porges, S. W. (1985). The relation between neonatal heart period patterns and developmental outcome. *Child Development, 56,* 28–37.

Garcia-Coll, C., Kagan, J., & Reznick, J. S. (1984). Behavioral inhibition in young children. *Child Development, 55,* 1005–1019.

Graham, F. K. (1973). Habituation and dishabituation of responses innervated by the autonomic nervous system. In H. V. S. Peeke & M. J. Herz (Eds.), *Habituation: Behavioral studies and physiological substrates* (pp. 163–218). New York: Academic Press.

Graham, F. K. (1979). Distinguishing among orienting, defense, and startle reflexes. In H. D. Kimmel, E. H. van Olst, & J. F. Orlebeke (Eds.), *The orienting reflex in humans* (pp. 137–167). Hillsdale, NJ: Erlbaum.

Graham, F. K., Anthony, B. J., & Zeigler, B. L. (1983). The orienting response and developmental processes. In D. Siddle (Ed.), *Orienting and habituation: Perspectives in human research* (pp. 371–430). Sussex, England: John Wiley.

Graham, F. K., Berg, K. M., Berg, W. K., Jackson, J. C., Hatton, H. M., & Kantowitz, S. R. (1970). Cardiac orienting response as a function of age. *Psychonomic Science, 19,* 363–365.

Graham, F. K., & Clifton, R. K. (1966). Heart-rate change as a component of the orienting response. *Psychological Bulletin, 65,* 305–320.

Graham, F. K., & Jackson, J. C. (1970). Arousal systems and infant heart rate responses. In H. W. Reese & L. P. Lipsitt (Eds.), *Advances in child development and behavior* (Volume 5, pp. 59–117). New York: Academic Press.

Grossman, P. (1983). Respiration, stress, and cardiovascular function. *Psychophysiology, 20,* 284–300.

Hagan, J. W. (1967). The effect of distraction on selective attention. *Child Development, 38,* 685–694.

Hallahan, D. P., & Reeve, R. E. (1980). Selective attention and distractability. In B. K. Keogh (Ed.), *Advances in special education. Volume 1: Basic constructs and theoretical orientations.* Greenwich, CT: JAI Press.

Harper, R. M., Hoppenbrouwers, T., Sterman, M. B., McGinty, D. J., & Hodgman, J. (1976). Polygraphic studies of normal infants during the first six months of life. I. Heart rate and variability as a function of state. *Pediatric Research, 10,* 945–961.

Harper, R. M., Scalabassi, R. J., & Estrin, T. (1974). Time series analysis and sleep research. *IEEE Transactions on Automatic Control, Vol AC-19, No 6,* 932–943.

Harper, R. M., Walter, D. O., Leake, B., Hoffman, H. J., Sieck, G. C., Sterman, M. B., Hoppenbrouwers, T., & Hodgman, J. (1978). Development of sinus arrhythmia during sleeping and waking states in normal infants. *Sleep, 1,* 33–48.

Hoppenbrouwers, T., Harper, R. M., Hodgman, J., Sterman, M. B., & McGinty, D. J. (1978). Polygraphic studies of normal infants during the first six months of life. II. Respiratory rate and variability as a function of state. *Pediatric Research, 12,* 120–125.

Horowitz, F. D., Paden, L., Bhana, K., & Self, P. (1972). An infant-control procedure for studying infant visual fixations. *Developmental Psychology, 7,* 90.

Kagan, J. (1982). Heart rate and heart rate variability as signs of a tempermental dimension in infants. In C. E. Izard (Ed.), *Measuring emotions in infants and children.* New York: Cambridge University Press.

Kagan, J., Kearsley, R., & Zelazo, P. (1978). *Infancy: Its place in human development.* Cambridge, MA: Harvard University Press.

Kagan, J., Reznick, J. S., Clarke, C., Snidman, N., & Garcia-Coll, C. (1984). Behavioral inhibition to the unfamiliar. *Child Development, 55,* 2212–2225.

Kahneman, D. (1973). *Attention and effort.* Englewood Cliffs, NJ: Prentice-Hall.

Karmel, B. Z., & Maisel, E. G. (1975). A neuronal activity model for infant visual attention. In L.

B. Cohen & P. Salapatek (Eds.), *Infant perception: From sensation to cognition* (Volume 1, pp. 77–131). New York: Academic Press.

Katona, P. G., Frasz, A., & Egbert, J. R. (1980). Maturation of cardiac control in full-term and preterm infants during sleep. *Early Human Development, 4,* 145–159.

Katona, P. G., & Jih, F. (1975). Respiratory sinus arrhythmia: Noninvasive measure of parasympathetic control. *Journal of Applied Physiology, 39,* 801–805.

Kearsley, R. B. (1973). The newborn's response to auditory stimulation: A demonstration of orienting and defensive behavior. *Child Development, 44,* 592–590.

Kero, P. (1974). Heart rate variation in infants with the Respiratory Distress Syndrome. *Acta Paediatrica Scandanavica,* Supplement 250.

Kinney, D. K., & Kagan, J. (1976). Infant attention to auditory discrepancy. *Child Development, 47,* 155–164.

Lacey, J. I., Kagan, J., Lacey, B., & Moss, H. (1963). The visceral level: Situational determinants and behavioral correlates of autonomic response patterns. In P. H. Knapp (Ed.), *Expression of the emotions in man* (pp. 161–196). New York: International Universities Press.

Lewis, M. (1971). A developmental study of the cardiac response to stimulus onset and offset during the first year of life. *Psychophysiology, 8,* 689–698.

Linnemeyer, S. A., & Porges, S. W. (1986). Recognition memory and cardiac vagal tone in 6-month-old infants. *Infant Behavior and Development, 9,* 43–56.

Lopes, O. U., & Palmer, J. F. (1976). Proposed respiratory 'gating' mechanism for cardiac slowing. *Nature, 264,* 454–456.

McCall, R. (1977). Challenges to a science of developmental research. *Child Development, 48,* 333–344.

Porges, S. W. (1974). Heart rate indices of newborn attentional responsivity. *Merrill-Palmer Quarterly, 20,* 231–254.

Porges, S. W. (1976). Peripheral and neurochemical parallels of psychopathology: A psychophysiological model relating autonomic imbalance in hyperactivity, psychopathology, and autism. In H. Reese (Ed.), *Advances in child development and behavior* (Volume 11, pp. 35–65). New York: Academic Press.

Porges, S. W. (1980). Individual differences in attention: A possible physiological substrate. In *Advances in special education* (Volume 2, pp. 111–134). Greenwich, CT: JAI Press.

Porges, S. W., Arnold, W. R., & Forbes, E. J. (1973). Heart rate variability: An index of attentional responsivity in human newborns. *Developmental Psychology, 8,* 85–92.

Porges, S. W., Bohrer, R. E., Cheung, M. N., Drasgow, F., McCabe, P. M., & Keren, G. (1980). New time-series statistic for detecting rhythmic co-occurrence in the frequency domain: The weighted coherence and its application to psychophysiological measures. *Psychological Bulletin, 88,* 580–587.

Porges, S. W., Bohrer, R. E., Keren, G., Cheung, M. N., Franks, G. J., & Drasgow, F. (1981). The influence of methylphenidate on spontaneous autonomic acitivity and behavior in children diagnosed as hyperactive. *Psychophysiology, 18,* 42–48.

Porges, S. W., & Humphrey, M. M. (1977). Cardiac and respiratory responses during visual search in nonretarded children and retarded adolescents. *American Journal of Mental Deficiency, 82,* 162–169.

Porges, S. W., McCabe, P. M., & Yongue, B. G. (1982). Respiratory-heart rate interactions: Psychophysiological implications for pathophysiology and behavior. In J. Caccioppo & R. Petty (Eds.), *Perspectives in cardiovascular psychophysiology* (pp. 223–264). New York: Guilford Press.

Porges, S. W., & Raskin, D. C. (1969). Respiratory and heart rate components of attention. *Journal of Experimental Psychology, 81,* 497–503.

Porges, S. W., Stamps, L. E., & Walter, G. F. (1974). Heart rate variability and newborn heart rate responses to illumination changes. *Developmental Psychology, 10,* 507–513.

Porges, S. W., Walter, G. F., Korb, R. J., & Sprague, R. L. (1975). The influences of methylphenidate on heart rate and behavioral measures of attention in hyperactive children. *Child Development, 46,* 727–733.

Richards, J. E. (1980). The statistical analysis of heart rate: A review emphasizing infancy data. *Psychophysiology, 17,* 153–166.

Richards, J. E. (1985a). Respiratory sinus arrhythmia predicts heart rate and visual responses during visual attention in 14 to 20 week old infants. *Psychophysiology, 22,* 101–109.

Richards, J. E. (1985b). The development of sustained visual attention in infants from 14 to 26 weeks of age. *Psychophysiology, 22,* 409–416.

Richards, J. E., & Rader, N. (1983). Affective, behavioral, and avoidance responses on the visual cliff: Effects of crawling onset age, crawling experience, and testing age. *Psychophysiology, 20,* 633–642.

Richards, J. E., & Turner, M. L. (1984). Structural models of infant heart rate and respiration and their relationship to visual and heart rate responses during attention. *Psychophysiology, 21,* 595 (Abstract).

Rose, S. A. (1983). Differential rates of visual information processing in full-term and preterm infants. *Child Development, 54,* 1189–1198.

Schiff, A. R., & Knopf, I. J. (1985). The effect of task demands on attention allocation in children of different ages. *Child Development, 56,* 621–630.

Schwartz, A. N., Campos, J. J., & Baisel, E. J. (1973). The visual cliff: Cardiac and behavioral responses on the deep and shallow sides at five and nine months. *Journal of Experimental Child Psychology, 15,* 86–99.

Sokolov, E. N. (1963). *Perception and the conditioned reflex.* New York: Macmillan.

Spyer, K. M. (1979). Baroreceptor control of vagal preganglionic activity. In C. M. Brooks, K. Koizumi, & A. Sato (Eds.), *Integrative functions of the autonomic nervous system* (pp. 283–392). Elsevier/North Holland Biomedical Press.

Von Bargen, D. M. (1983). Infant heart rate: A review of research and methodology. *Merrill-Palmer Quarterly, 29,* 115–149.

Vranekovic, G., Hock, E., Isaac, P., & Cordero, L. (1974). Heart rate variability and cardiac response to an auditory stimulus. *Biology of the Neonate, 24,* 66–73.

Walter, G. F., & Porges, S. W. (1976). Heart rate and respiratory responses as a function of task difficulty: The use of discriminant analysis in the selection of psychologically sensitive physiological responses. *Psychophysiology, 13,* 563–571.

Wastell, D. G. (1981). Measuring heart rate variability: Some comments on the successive difference mean square statistic. *Psychophysiology, 18,* 88–90.

Watanabe, K., Iwase, K., & Hara, K. (1973). Heart rate variability during sleep and wakefulness in low-birthweight infants. *Biology of the Neonate, 22,* 87–98.

Wickens, C., Kramer, A., Vanasse, L., & Donchin, E. (1983). Performance of concurrent tasks: A psychophysiological analysis of the reciprocity of information-processing resources. *Science, 221,* 1080–1082.

Williams, T. A., Schacter, J., & Tobin, M. (1967). Spontaneous variation in heart rate: Relationship to average evoked heart rate response to auditory stimuli in the neonate. *Psychophysiology, 4,* 104–111.

Wohlwill, J. (1973). *The study of behavioral development.* New York: Academic Press.

Womack, B. F. (1971). The analysis of respiratory sinus arrhythmia using spectral analysis and digital filtering. *IEEE Transactions on Biomedical Engineering, 18,* 399–409.

Zelazo, P. R., & Kearsley, R. B. (1982). Memory formation for visual sequences: Evidence for increased speed of processing with age. *Infant Behavior and Development, 5,* 263.