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Infant Heart Rate: A Developmental Psychophysiological Perspective

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Introduction

Psychophysiology is the study of the relation between psychological events and biological processes in human subjects. The electrocardiogram (ECG) and heart rate (HR) have been commonly used measures throughout the history of psychophysiological research. Early studies found that stimuli eliciting differing emotional responses in adults also elicited HR responses differing in magnitude and direction of change from baseline (e.g., Darrow, 1929; Graham & Clifton, 1966; Lacey, 1959). Vast improvements in methods of measuring ECG and knowledge regarding the relationship between HR and cognitive activity have occurred.

Heart rate has been particularly useful in developmental psychophysiological research. Researchers interested in early cognitive and perceptual development have utilized HR as a window into cognitive activity for infants before they are capable of demonstrating complex behaviors or providing verbal responses. Also, the relation between brain control of HR and the behavior of HR during psychological activity has helped work in developmental cognitive neuroscience. In this chapter, we address the use of the ECG and HR in research on human infants. We review research utilizing three ways in which HR has been used in this work: HR changes, attention phases defined by HR, and HR variability (particularly respiratory sinus arrhythmia). Topics we will focus on are: the areas of the brain that are indexed with these measures, developmental changes associated with these measures, and the relationship of these measures to psychological processes. Before covering research with infants, we will briefly review background information on the heart, the ECG and HR, and its relation to psychophysiology.

The Heart, the Electrocardiogram and Heart Rate, and Heart Rate Psychophysiology

The heart, which is the strongest muscle in the human body, is composed of three layers of tissue. The outermost layer of tissue is the epicardium. This layer contains coronary vessels and the cardiac autonomic nerves. The middle layer of tissue, known as the myocardium, is composed of layers of muscle tissue. The endocardium lines the inner walls of the heart chambers. Cells of the endocardium are smooth, offering little resistance to circulation. The four chambers that compose the heart are the left and right atria, which serve as reservoirs for incoming blood; and the left and right ventricles, which together provide the majority of pumping force for the heart (Hassett & Danforth, 1982).

The heart muscle contracts at regular intervals, i.e., the heart beat. Figure 1 shows a schematic illustration of the heart and the areas involved in the heart beat (Andreassi, 1989). The beat occurs by the spread of spontaneously-originating electrical activity through the sinoatrial (SA) node, atrial bundles, the atrioventricular (AV) node, the bundle of His, and the Purkinje networks. Cells within these specialized conduction tissues spontaneously depolarize and generate an action. The SA node is made up of a small group of cells within the walls of the right atrium. These cells have a resting membrane potential that is lower than other cardiac pacemaker cells. The cells of the SA node depolarize and repolarize at a faster discharge rate than other cardiac cells because of this lower resting membrane potential. Thus, normally the SA node serves as the location of the cardiac pacemaker.

The ECG is a record of the electrical activity produced as action potentials are generated in the SA node of the right atrium. Figure 1 shows a representation of the heart and how the components of the ECG are related to the events in the heart beat. A single cardiac cycle is represented in the ECG as a characteristic waveform comprised of four waves and three primary intervals (Brownley, Hurwitz, & Schneiderman, 2000). The P-wave represents atrial depolarization beginning at the SA node and spreading in all directions over the atrial muscle. Ventricular depolarization is conducted from the endocardial tissue to the epicardial tissue of the left ventricle and is represented in the ECG by the R-wave. Further depolarization of the right ventricle occurs at the S wave. Finally, The T-wave represents the completion of depolarization and the

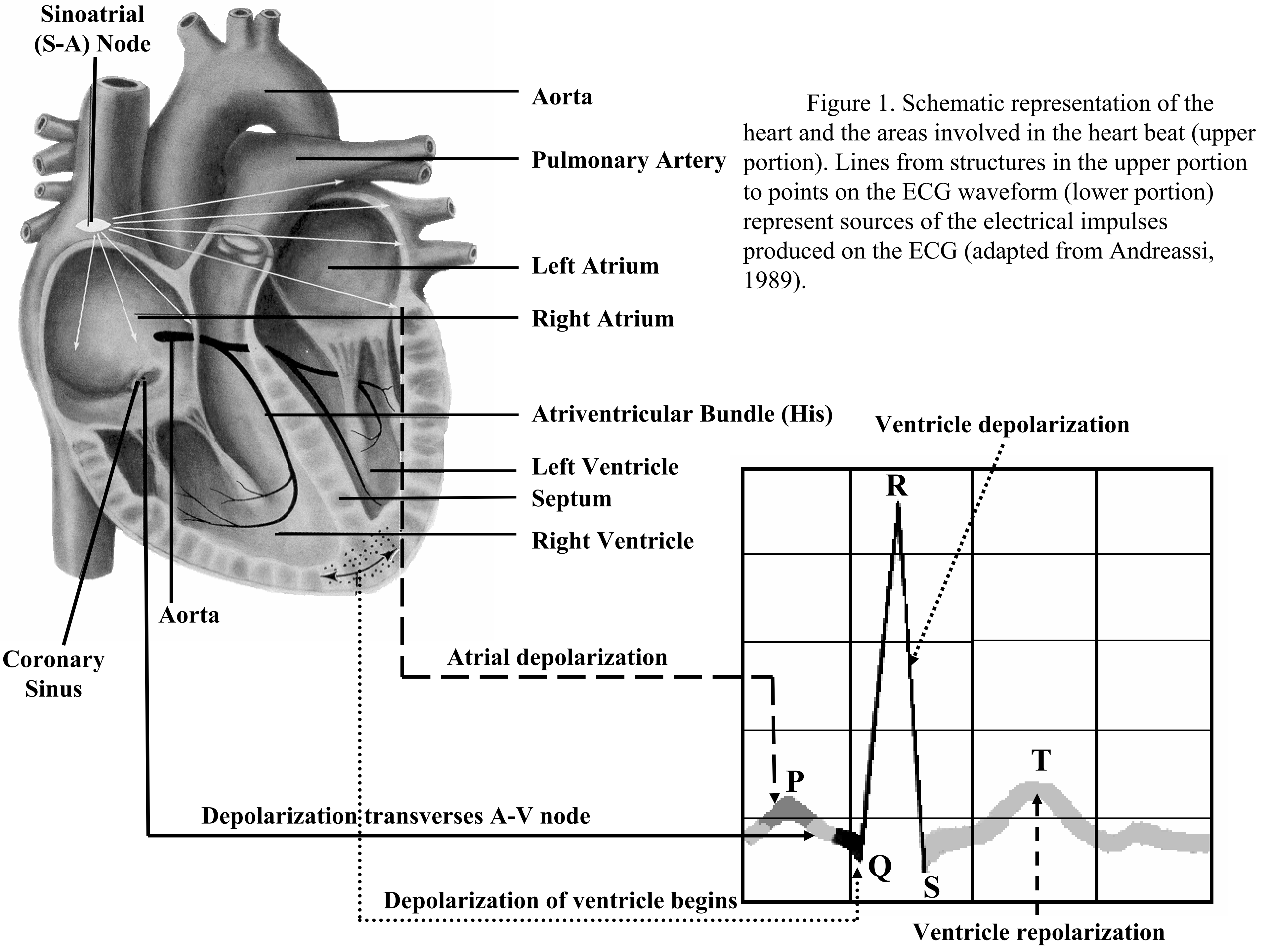

Figure 1. Schematic representation of the heart and the areas involved in the heart beat (upper portion). Lines from structures in the upper portion to points on the ECG waveform (lower portion) represent sources of the electrical impulses produced on the ECG (adapted from Andreassi, 1989).

beginning of repolarization (Smith & Kampine, 1984). The three intervals are identified by the waves that they occur between. The P – R interval signifies the passage of the action potential from the atrium to the ventricular muscle. The early part of this interval (from the P-wave to the Q-wave) represents the spread of the cardiac impulse through the AV node. The Q – T interval reflects the process of ventricular depolarization and repolarization.

Einthoven pioneered the use of the ECG for recording cardiac potentials in the early part of the 20th Century. The ECG is recorded by placing electrodes on two surface points (bipolar recording) of the tissue of the body surrounding the heart. Because body tissues conduct electricity, a constant fraction of the cardiac potential will be picked up between these two electrodes. The ECG is the sum of all the action potentials that occur during depolarization of the myocardial tissue of the heart. This potential is then amplified and recorded. Depolarization toward an electrode produces positive potential and depolarization away from an electrode produces negative potentials in the ECG recording. The classical method of measuring ECG is to record from three electrodes placed on three extremities of the body. The most common placement of electrodes is the left and right arms and the left or right leg (which is used as a reference electrode). Use of this three-lead configuration is based upon Einthoven's equilateral triangle (Einthoven, Fahr, & de Waart, 1913), a configuration of leads that records the activity of the heart within a 2D geometric figure (Brownley, Hurwitz, & Schneiderman, 2000). This configuration records the primary waves of the ECG waveform as positive potentials.

The classic three lead configuration is modified in infants by placing electrodes on the right and left chest area and the right abdomen (used as a reference electrode). Figure 2 shows an infant with the chest leads and electrooculogram (EOG) recording (Richards, 1998, 2000). This method provides good ECG recordings and is less sensitive to movement artifact produced by movement of the arms and legs. An alternative configuration is to place the two active electrodes on the chest and back. Either configuration serves to provide good ECG recordings and are less sensitive to movement artifact than placement on the limbs. The reference lead may also be placed in the center of the chest between the right and left chest leads for use with infants.

Quantification of Heart Rate

The ECG is the electrical signal produced by the heart and represents the events occurring during the cardiac cycle. However, psychophysiological use of the ECG itself is rare. Rather, some measure of the length of the cardiac cycle is derived from the ECG and used in psychophysiological research.

The length of the cardiac cycle is often expressed as "interbeat-interval" (IBI, in ms units). This also is termed "heart period", i.e., the period of the cardiac cycle. The IBI can be determined by measuring each occurrence of a specific component of the ECG waveform. The most common point of the cardiac cycle used when measuring heart period is the peak of the R-wave. The R-wave is most commonly used to calculate the time between cardiac cycles because it is manifested as a sharp positive peak followed by a negative deflection in the ECG waveform. The peak of the R-wave is normally greater in amplitude than all other peaks making it is easily discriminable from other components of the cardiac cycle. Thus, IBI is often defined as the duration between successive R-waves (R-R interval).

Heart rate is the number of beats in a period of time, and its units are "beats-per-minute" (BPM). Heart rate can be calculated by counting the beats in some period of time. However, it is most conveniently calculated as the inverse of the IBI (60000 / IBI ms). Most early work with "cardiac cycle length" used HR as the measure of quantification. Some methodological issues suggest that IBI is a better quantification than HR for psychophysiological research. There has been some discussion about the use of time or beats as the appropriate domain for the quantification. Typical use quantifies the data as a function of time rather than beats. We will use the term "heart rate" in this chapter synonymously for HR or IBI, i.e., changes in cardiac cycle length whether they are decreased HR (longer IBIs) or increased HR (shorter IBIs). The direction of the cardiac cycle length is the underlying biological process that is changing regardless of using the IBI or HR terminology.

Brain Influences on Heart Rate

The influence of the central nervous system upon HR is mediated by the sympathetic and parasympathetic nervous systems. Sympathetic nervous system impulses increase HR through a pressor effect triggered

Figure 2. Picture of an infant with HR and EOG leads. The two leads located on the chest along with an additional reference lead placed on the right abdomen area (not seen in picture) are used for ECG recording. The leads located in the facial area are used for EOG recording (Richards, 1998, 2000).

by the release of adrenalin (Hassett & Danforth, 2000). The sympathetic innervation of the heart originates through axons originating in the intermediolateral cell column of the spinal cord. Activity in the sympathetic nervous system increases the rate of depolarization in the pacemaker cells, shortens the interval between beats, and results in increased HR. The parasympathetic nervous system decreases heart activity through the release of acetylcholine on the SA node. The parasympathetic innervation of the heart comes from neurons in the 10th cranial nerve, the vagus. Activity in the parasympathetic nervous system releases acetylcholine on the SA node, slowing the depolarization of the pacemaker cells, increasing the length of the interval between the T and the P wave, and thus results in HR decreases. The ventrolateral medulla, dorsal motor nucleus of the vagus nerve, and the nucleus ambiguus are primarily responsible for the parasympathetic nervous system influence on HR. The bidirectional nature of HR does not necessarily lead to correct inferences about whether parasympathetic or sympathetic activity is causing HR change. Slowing of HR may be caused by activation of the parasympathetic system or withdrawal of the sympathetic system. Increases in HR may be caused by parasympathetic withdrawal or sympathetic system activity.

The impact of cerebral cortex on HR is of particular interest for psychophysiological research. This is due to the role of the cerebral cortex in processing sensory information and cognitive information processing, which in turn influences autonomic functioning. Structures within the central nervous system that impact the cardiovascular system can be found within the spinal cord, hindbrain, and forebrain. The hypothalamus and cerebral cortex (forebrain structures) influence HR (Brownley, Hurwitz, & Schneiderman, 2000).

One particularly interesting CNS influence is a cardio-inhibitory system found in the frontal cortex, limbic system, and the mesencephalic reticular activating system. Stimulation of the reticular activating system evokes low voltage high frequency desynchronized electrical activity throughout the cortex that is associated with alert wakefulness and vigilance (Moruzzi & Magoun, 1949; Starzl, Taylor, & Magoun, 1951). Other components of this system are involved in auditory and visual perception, and attention (Posner, 1995; Posner & Petersen, 1990). Richards (2001) shows how this system is linked to a general arousal system involving the mesencephalic reticular activating system (Heilman, Watson, Valenstein, & Goldberg, 1987; Mesulam, 1983) and the neurochemical systems controlling arousal (Richards, 2001; Robbins & Everitt, 1995). This general arousal system has an ascending influence on cortical areas and enhances processing and arousal. This same system has a descending influence on HR through a parasympathetic outflow and decreases HR in infants and children, or decreases HR variability in adults. Thus, extended HR slowing is an index of a state of general arousal in the brain.

A well-known variability in HR called “respiratory sinus arrhythmia” (RSA) has a well-known nervous system control. Respiratory sinus arrhythmia is variability in HR that is coincident with respiration. It is an “arrhythmia” because it disrupts the constant rate of the sinus rhythm caused by the pacemaker cells in the SA node. Accelerations and decelerations in HR occurring in this frequency band occur at the same rate of respiration inhalations and exhalations (Porter, Bryan, & Hsu, 1995; Richards & Casey, 1992). The respiratory control centers in the brainstem and midbrain alternately inhibit and disinhibit the nucleus ambiguus of the vagus nerve (Anrep, Pascual, & Rossler, 1935; Berntson, Cacioppo, & Quigley, 1993; Katona & Jih, 1975; Porges, McCabe, & Yongue, 198; Reed, Ohel, David, & Porges, 1999). This results in a cyclical outflow of acetylcholine to the SA node, alternatively speeding (during inspiration and vagal inhibition) and slowing (during expiration and vagal disinhibition) HR. The parasympathetic nervous system thus solely mediates RSA activity.

Heart Rate in Psychophysiology

As has been the case for many areas of psychophysiological research, infant HR studies emerged out of a history of research utilizing ECG in adult populations. Darrow (1929) was one of the first researchers to utilize HR in psychophysiological research. Darrow concluded that HR and blood pressure change associated with stimulus exposure was due to associative processes linked with emotion. Other early adult studies focused on the HR response as a component of Sokolov’s (1963) orienting reflex (Davis, Buchwald, & Frankmann, 1955; Zeaman, Deane, & Wegner, 1954). The orienting reflex is the first response of an organism to a stimulus. The orienting response is composed of specific behavioral reactions, as well as changes in central and autonomic nervous system activity that reflect alterations in the organism's general level of arousal. These alterations in arousal level are associated with attending to an environmental stimulus. Sokolov argued that these physiological responses amplify or reduce the effects of sensory stimulation by acting directly on sensory receptors and indirectly through feedback to central mechanisms, ultimately having major effects on learning and perceptual processes. Sokolov differentiated the orienting reflex from the defensive reflex. The orienting reflex is associated with a decrease in sensory thresholds, whereas the defensive reflex is a generalized response system associated with an increase in sensory thresholds. In Sokolov's view, increased sympathetic activity had a facilitating effect on information processing by maintaining cortical activation. While Sokolov's own work with the orienting reflex did not focus on HR as a component of the response, it was assumed that the HR component of the orienting reflex would take the form of an acceleratory response.

Lacey (1959) was involved with HR research and developed the concept of "directional fractionation" to replace contemporary views of arousal as a global phenomenon. Directional fractionation refers to Lacey's finding that different fractions of the total somatic response pattern may respond in different directions. Thus, although cortical areas may become activated, HR may decelerate. In fact, Lacey and Lacey (1958) proposed an "intake-rejection" hypothesis stating that increased HR was associated with inhibition of cortical activity. The authors proposed that this physiological response was likely to occur in situations where stimulation is unpleasant or painful, thus facilitating a "rejection" of environmental information. However, in situations where attention is called for, decreases in HR associated with increased sensitivity to stimulation are found to occur (Lacey, 1959; Lacey, Kagan, Lacey, & Moss, 1962). In other words, decreased HR is associated with a decrease in sensory thresholds, and increased HR is associated with an increase in sensory thresholds.

Graham & Clifton (1966) noted that Sokolov's hypothesis regarding the orienting reflex and the Laceys' intake-rejection hypothesis were consistent with one another except in the interpretation of the role of HR changes. Recall that Sokolov assumed the orienting reflex was associated with HR accelerations. The authors proposed that two possibilities could explain the contrasting interpretations of HR changes: (1) HR acceleration is a phasic component and HR deceleration is a tonic component of the orienting reflex, or (2) HR acceleration is part of the defense reflex and HR deceleration is a part of the orienting reflex. After reviewing the literature and focusing on studies that utilized simple stimuli appropriate for eliciting an orienting reflex, it was concluded that HR deceleration is a component of the orienting reflex and HR acceleration is a component of the defense reflex.

Infant Heart Rate Studies

Much of the early research utilizing infant HR focused on the ability of infants of differing ages to demonstrate the orienting reflex. Several studies utilizing 75 db auditory stimulation revealed acceleratory HR responding in newborns (Chase, 1965; Graham & Keen, 1965; Keen, Chase, & Graham, 1965). Davis, Crowell, and Chun (1965) found that newborns responded with HR accelerations to tactile and olfactory stimulation in addition to auditory stimulation. In a longitudinal analysis conducted by Lipton and Steinschneider (1964), it was found that infants that demonstrated an acceleratory response at birth demonstrated decelerations in HR to the same stimuli at 2, 4, and 5 months of age. These findings led researchers at the time to conclude that newborns were unable to demonstrate the orienting reflex and responded solely with the defense reflex or startle responses. However, Graham and Jackson (1970) noted that the stimuli used in prior newborn studies were not appropriate for eliciting orienting responses in newborns – abrupt onsets had been utilized with intense stimuli in many cases. Additionally, the behavioral state of the infants had not been controlled during testing procedures. Subsequent research revealed that the direction and magnitude of HR change was dependent, in part, upon the behavioral state of the infant. For example, stimuli that evoke HR decreases in awake newborns have been found to evoke HR accelerations during sleep (Clifton & Nelson, 1976; Pomerleau & Malcuit, 1981; Pomerleau-Malcuit & Clifton, 1973). Only newborns in the awake state have been found to exhibit sustained decreases in HR (Graham, Anthony, & Zeigler, 1983). Furthermore, stimulus complexity and intensity appear to interact in determining the direction of HR responses in newborns. Simple auditory stimuli presented at 75-80 dB elicit HR decelerations while complex auditory stimuli of equivalent intensity elicit HR accelerations (Clarkson & Berg, 1983; Fox, 1979). Newborns also show larger and longer decelerations in HR following presentations of stimuli they visually prefer (e.g., horizontal versus vertical grating, novel versus familiar stimuli; Lewis, Kagan, Campbell, & Kalafat, 1966; McCall, & Kagan, 1967).

Heart rate responses have been found to change with age. Infants are more likely to display HR decelerations following stimulus exposure with increasing age across the first year of postnatal development. While newborns demonstrate HR accelerations following exposure to air puff streams, HR decelerations are consistently found for 2.5-month-olds following air stream exposure (Davis, Crowell, & Chun, 1965; Berg & Berg, 1979). Similarly, the magnitude of HR decelerations to a 75 dB, 1000 Hz tone increases with age from birth to 10 months (Berg, 1975; Graham, Berg, Berg, Jackson, Hatton, & Kantowitz, 1970). Figure 3 shows a graph of HR responses to a 2 s tone, and HR responses to a startle pulse of white noise as a function of age (Graham et al., 1970; Graham, Fik, Strock, & Zeigler, 1981; Graham et al., 1983). Infants' heart rate response to a 2 s tone of moderate intensity (75 dB) takes the form of the orienting reflex (figure 3, left panel) that increases in magnitude from birth to 16 weeks of age. In contrast, HR responding to a more intense (109 dB) auditory stimulus (figure 3, right panel) takes the form of the defensive reflex in 6-week-olds but shifts to a heart rate deceleration (orienting reflex) of increasing magnitude from 12 to 24 weeks of age. Adults demonstrate heart rate responses of much lesser magnitude than infants regardless of the direction of the response.

Many of the early studies of infant HR responses utilized brief stimuli. These types of stimulus presentations elicit relatively short duration responses. Berg & Berg (1979) noted the importance of discriminating between brief and sustained HR decelerations. Brief decelerations may reflect an immature, subcortically mediated orienting reflex or an automatic interrupt component of orienting (Graham, 1979). If this is the case, then information processing associated with orienting and attention would be expected to occur during periods of sustained decreases in HR. Research has expanded upon the relationship between HR and various components of attention and information processing in infants.

One line of work showing extended changes in HR to stimuli has been the study of children's attention to television programs (Richards & Cronise, 2000; Richards & Gibson, 1997; Richards & Turner, 2001). Rather than brief stimuli, infants and young children from 3 months to 2 years of age were presented with recordings of a "Sesame Street" movie, computer-generated geometric patterns, and similar visual stimuli. These presentations were accompanied by sound. One visual response to such stimuli are extended fixations, lasting for some occurrences up to 2 min in length. It has been hypothesized that during such long looks there is an increase in attention engagement over the course of the look (Richards & Anderson, in press). Heart rate changes have been used in adult participants to index attentiveness to television programs (e.g., Lang, 1990; Reeves, Thorson, Rothschild, McDonald, Hirsch, & Goldstein, 1995). The studies of infants' and children's extended television viewing showed a typical HR deceleration as if the orienting response occurred (e.g., Figure 3). Figure 4 shows the heart rate changes that occur in children from 6-months to 2-years of age during extended viewing (Richards & Cronise, 2000). The extended looks were accompanied by increasingly deep heart rate changes. These changes in heart rate also are associated with an increasing resistance to distraction by a peripheral stimulus (Richards & Turner, 2001). The extended slowing of HR accompanying these extended looks imply that there is an increase over the course of such looks in the extent of attentional engagement (Richards & Anderson, in press).

Resting HR decreases with age during infancy (Bair-Haim, Marshall, & Fox, 2000; Izard, Porges, Simons, Haynes, Hyde, Parisi, & Cohen, 1991). Heart rate also shows consistent individual differences in early development. Bar-Haim et al. (2000) found that resting HR at 4 months of age was significantly correlated with HR at 14, 24, and 48 months of age. However, there are specific time periods during the first year that appear to be periods of transition in which instability is found in HR measures. The first of these periods is around 6 weeks of age. It is more difficult to elicit HR deceleration at this age than at earlier and later ages (Figure 3; Brown, Leavitt, & Graham, 1977; Graham, Anthony, & Zeigler, 1983). This period of instability may reflect a shift from a predominance of subcortical to cortical control of orienting (Field, Muir, Pilon, Sinclair, & Dodwell, 1980). Beginning at around 4 months of age

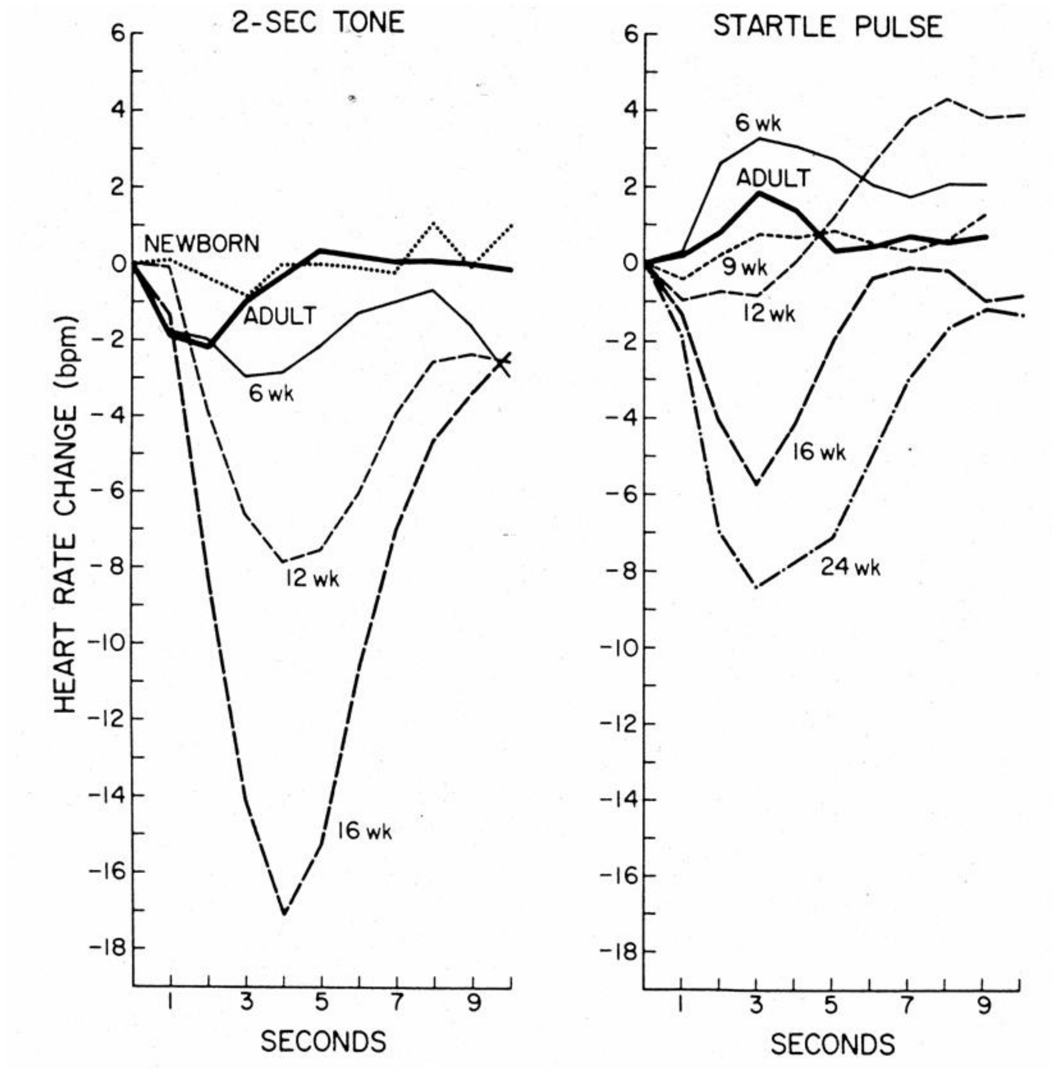

Figure 3. Changes in HR response as a function of age to a 2-s 75-dB, 1000 Hz tone (left panel; Graham et al., 1970). HR responding as a function of age to a 50-ms white noise startle pulse at 104 dB for adults and 109 dB for infants (right panel; Graham et al., 1981, 1983).

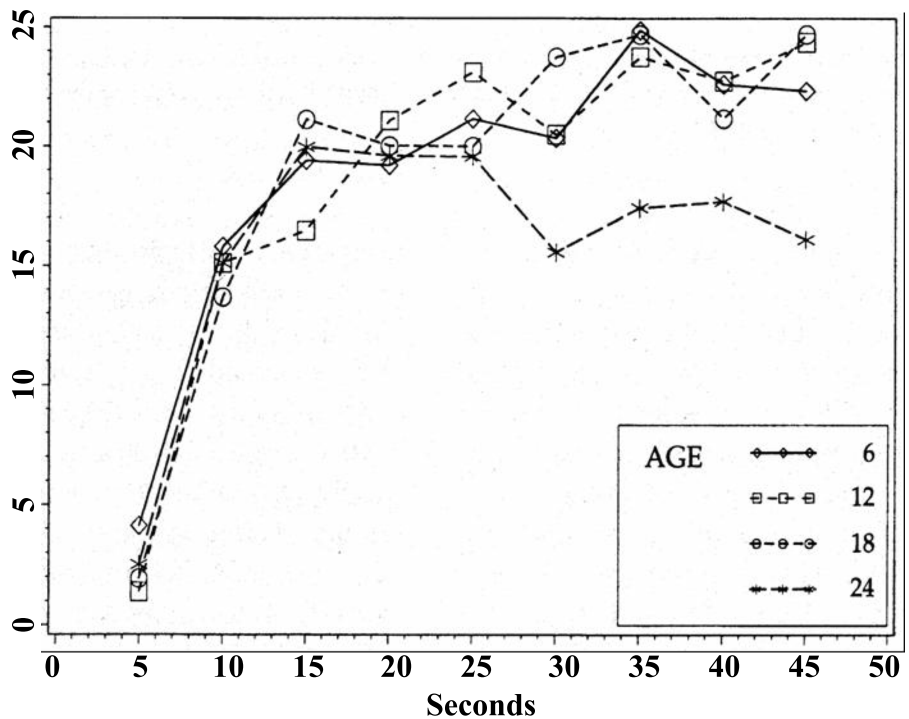

Figure 4. The change in IBI length (mean 5-s IBI – average prestimulus IBI) as a function of the duration of the fixation for the four testing ages, averaged across all look length categories. This figure is combined for the "Sesame Street" movie and the mixed-stimuli session. The last 5 s of the look was not included in these averages (Richards & Cronise, 2000).

and lasting for several months, infants show reliable increases in HR orienting (HR deceleration) and decreases in resting HR. However, Bar-Haim et al. (2000) found that HR at 9 months of age was not correlated with HR at any other age measured. This is a time when the developmental trend of decreasing HR begins to slow, and this may explain the lack of correlation between 9 month HR and HR measured at earlier and later ages. This also may reflect a cognitive transition. Areas of frontal cortex (e.g., dorsolateral frontal cortex, orbito-frontal cortex) are becoming more functionally mature at this time, and this is reflected by gains in performance on tasks measuring attention and memory (e.g., Bell, 1998; Diamond, Prevor, Callender, & Druin, 1997; Diamond, Cruttenden, & Niederman, 1994).

Attention Phases defined by Infant HR

Several researchers have proposed that HR measures can be used to index four phases of information processing (Graham, 1979; Graham, Anthony, & Ziegler, 1983; Porges, 1976, 1980; Richards, 1988a, 2001; Richards & Casey, 1992; Richards & Hunter, 1998). These phases are the automatic interrupt, stimulus orienting, sustained attention, and attention termination. Changes in HR that are linked with visual fixation may be used as a means of determining which phase of attention an infant is engaged. The HR changes associated with the latter three phases of attention are depicted in Figure 5 for young infants. The pre-attention period simply depicts the time before the presentation of the visual stimulus. The pre-attention termination period is an artifact of operational definitions of attention termination (cf. Richards & Casey, 1992).

The automatic interrupt phase is the first of the information processing phases (Graham, 1979). During this phase, the infant is involved in detecting transient changes in environmental stimulation. This phase may or may not be followed by further processing of the novel information provided by the transient changes in the environment. A brief bi-phasic HR response (deceleration-acceleration) occurs in cases in which information processing is terminated. In these cases, the automatic interrupt system is manifested as a startle reflex. The automatic interrupt system is obligatory, and is under the control of short-latency nervous system pathways (Richards & Casey, 1992).

Stimulus orienting is the second HR phase of attention. This phase is controlled by long-latency pathways within the nervous system. Stimulus orienting is activated by the automatic interrupt phase and is identical to the orienting reflex studied by Sokolov (1963; cf. Graham & Clifton, 1966). The stimulus orienting system is similar to the automatic interrupt system in that both are reflexive and follow the same time course regardless of subsequent input. A large deceleration in HR lasting about 5 seconds is indicative of activation of the stimulus orienting system. Stimulus orienting is an early phase of information process in which the infant evaluates stimulus novelty, processes preliminary stimulus information, and decides whether to allocate further mental resources (Kahneman, 1973). The magnitude of HR deceleration is related to the novelty of the stimulus being processed by the infant.

Sustained attention is the third HR phase of attention (Porges, 1976, 1980; Richards, 1987, 1988a, 2001; Richards & Casey, 1992; Richards & Hunter, 1998). In contrast to the preceding phases, sustained attention involves voluntary, subject-controlled cognitive processing. Heart rate shows a sustained decrease from baseline, has decreased levels of variability, and is accompanied by decreased respiration amplitude, inhibition of body movements, and other bodily changes during sustained attention (Jennings, 1986). Sustained attention begins 4-5 seconds following visual fixation. The duration of this phase depends on the state of the infant, the relative novelty of the stimulus, stimulus complexity, and characteristics of the subject. Sustained attention may last from 2-3 seconds to 20 seconds or longer. This phase of attention is the phase in which the majority of information processing occurs.

The final HR attention phase is attention termination (Richards, 1988a, 1988b; Richards & Casey, 1992; Richards & Hunter, 1998). Heart rate returns to baseline levels and variability. Behaviorally, the infant continues to fixate on the stimulus during attention termination. However, the infant is no longer processing information in the stimulus. Attention termination endures for approximately 6 seconds (Casey & Richards, 1991; Richards & Casey, 1990).

These attention phases are probably controlled by a variety of brain areas. The initial deceleration of HR during stimulus orienting is mediated by the parasympathetic nervous system. The CNS areas that control such changes are likely areas of the brain involved in sudden

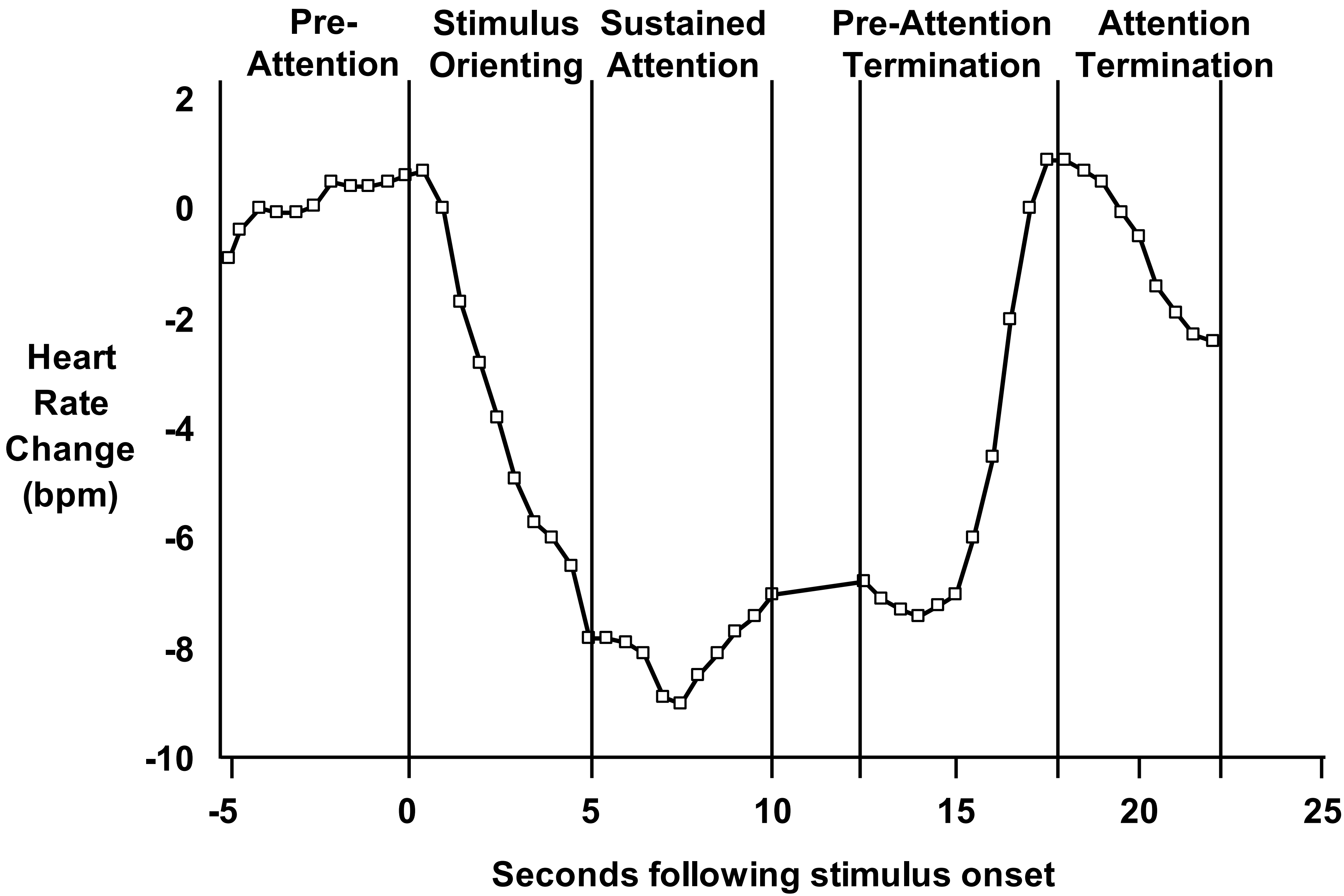

Figure 5. Average HR change as a function of seconds following stimulus onset during the HR-defined attention phases (Richards & Casey, 1992).

arousal or orienting, such as the mesencephalic reticular activating system (Heilman, Watson, Valenstein, & Goldberg, 1987; Mesulam, 1983). If such an orienting in the CNS leads to continued processing of the stimulus, sustained attention begins and a second CNS system is engaged. This system is a general arousal system associated with alertness and vigilance. The arousal system in the CNS is mediated by neurochemical systems that energize cortical systems (Richards, 2001; Robbins & Everitt, 1995). The neural basis for attention termination is unknown. Perhaps there is a refractory period in the attentional system that inhibits its engagement for a short period of time following sustained attention (Casey & Richards, 1991). Alternatively, it may simply be that at the end of sustained attention it takes some measurable amount of time for a new HR deceleration to occur. In this case, attention termination would simply be the cessation of the brain's arousal state before attention was yet engaged.

Relation between Heart Rate and Behaviorally Defined Attention Phases

Differing types of attention in young infants have been found using behavioral measures of attention engagement. "Focused attention" is a period of time when infants are actively examining objects (Oakes, Madole, & Cohen, 1991). Ruff (1986) defined attentive fixation as looking combined with fingering or turning the object about with an intent facial expression. "Casual attention" is a period of time when fixation is directed toward a stimulus or object, but the infant is not actively examining the stimulus. As with the attention phases defined by HR, these attention phases occur within the course of a single look towards a stimulus, or an episode of play with a toy.

The implications for information processing of focused and casual attention are similar to those of sustained attention and attention termination. Focused attention and casual attention are behaviorally defined periods of attention and inattention. Sustained attention and attention termination are HR defined periods of attention and inattention. Infants take longer to disengage from a central stimulus and shift attention to a distractor stimulus during focused attention than during casual attention (Oakes & Tellinghuisen, 1994; Ruff, Capozzoli, & Saltarelli, 1997; Tellinghuisen & Oakes, 1997). Similarly, infants demonstrate longer distraction latency to a peripheral stimulus presented during sustained attention than during attention termination (Casey & Richards, 1988; Hunter & Richards, 2003; Richards, 1987, 1997b). Sustained attention and focused attention are operationally defined phases of attention that represent periods when the infant is actively engaged in information processing. Distraction latencies are longer when infants are engaged in these phases of attention because infants are processing information provided by a central stimulus. During casual attention or attention termination infants respond more rapidly to peripheral stimuli because they are no longer engaged in attention to the central stimulus.

Lansink and Richards (1997) conducted a study aimed at establishing a link between behaviorally defined and HR defined phases of attention. Infants of 6, 9, and 12 months of age were tested. Infants were seated on a parent's lap at a table. A TV monitor was located 45° to the right of the infant. The infant was allowed to play freely with a toy secured to the top of the table with suction cups. At various times during play sessions dynamic computer generated patterns were presented on the TV monitor as a distractor stimulus. Once the infant localized the distractor, the monitor was turned off, marking the end of the trial. For each distractor, either HR or behavior was used to determine if the infant was attentive (HR: sustained attention; behavior: focused attention) or inattentive (HR: attention termination; behavior: casual attention).

There were several interesting findings. Figure 6 shows the distraction latencies for infants when attentive or inattentive defined by behavior, HR, or a combination of the two. Infants had longer distraction latencies during focused attention than during casual attention. Infants also demonstrated longer distraction latencies during sustained attention than attention termination, replicating past findings from studies. These findings replicate several studies (Oakes & Tellinghuisen, 1994; Ruff et al., 1997; Casey & Richards, 1988; Richards, 1987). When HR and behavioral measures were concordant for attentiveness, the infants showed the longest distraction latencies, and when the measures were concordant for inattentiveness, the shortest distraction latencies (Figure 6, right panel). In addition to the distraction latencies, the HR deceleration on the focused attention trials were larger than on the casual attention trials (Figure 7, left panel). These findings show a large overlap between attentional status defined by HR changes, and attentional status defined by behavioral indices.

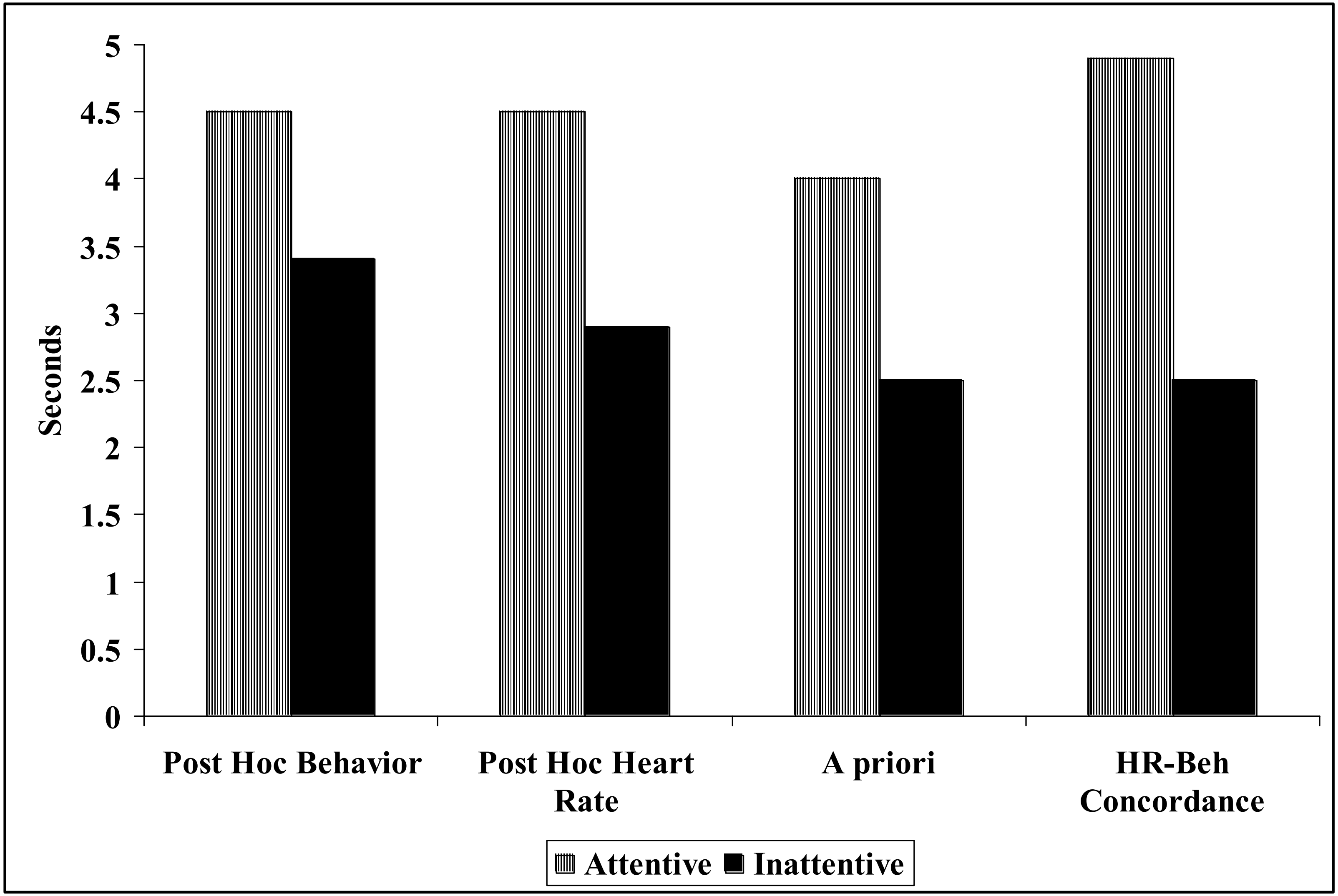

Figure 6: Distraction latency for engaged (shaded bars) and unengaged (solid bars) trials. This is shown separately for the trials defined online with HR or behavior ("A priori"), for trials defined post hoc with behavior, post hoc with HR, or post hoc when HR and behavior indices were in concordance. (Lansink & Richards, 1997).

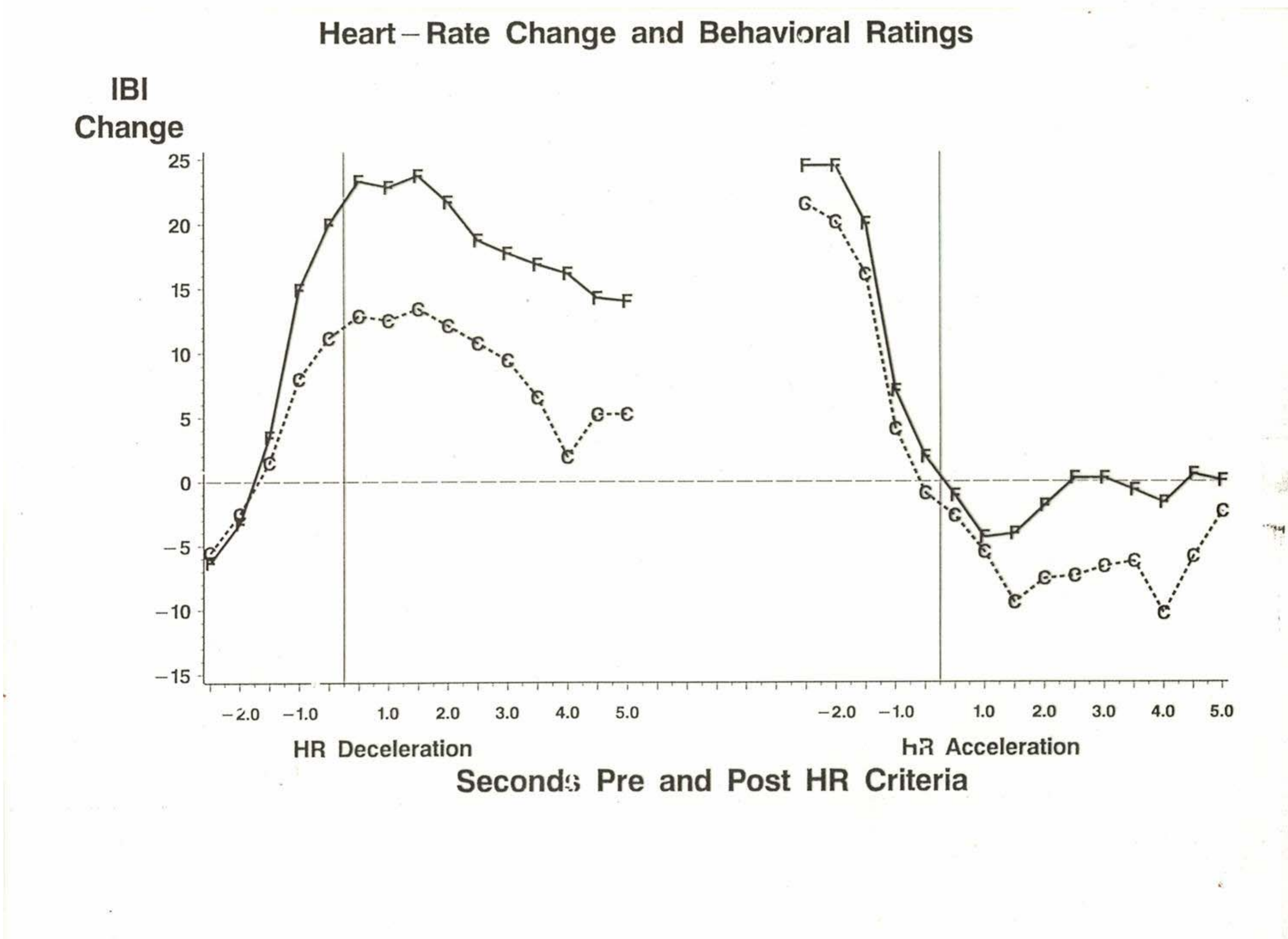

Figure 7: Changes in IBI when heart rate and behavioral measures of attention are congruent and incongruent. Heart rate 2.5 s before through 5 s after the heart rate deceleration and heart rate acceleration criteria were met (C: Casual attention behavioral rating; F: Focused attention behavioral rating.). (Lansink & Richards, 1997).

Heart Rate Phases and Distractibility

Developmental psychophysiologists have investigated peripheral stimulus localization in infants for several decades. Early research in this area used peripheral stimulus localization as a means of determining the effective visual field of infants of varying ages (Aslin & Salapatek, 1975; de Schonen McKenzie, Maury, & Bresson, 1978; Harris & MacFarlane, 1974; MacFarlane, Harris, & Barnes, 1976; Tronick, 1972). As age increases in early development, infants will demonstrate fixation shifts of increasing eccentricity from a central stimulus to a peripheral stimulus. This increase in the eccentricity at which an infant will shift fixation from a central to peripheral stimulus was interpreted as an increase in the size of the effective visual field with age. Subsequent research has utilized peripheral stimulus localization as a measure of infant attention to a central stimulus (Atkinson, Hood, Braddick, & Wattam-Bell, 1988; Atkinson, Hood, Wattam-Bell, & Braddick, 1992; Hood & Atkinson, 1993; Richards, 1987, 1994; Richards & Casey, 1992). The logic behind this approach is partially based upon the finding that infants demonstrate greater localization eccentricities to peripheral stimuli when no central stimulus is used or the central stimulus is turned off than in competitive situations when the central stimulus remains on after presentation of the peripheral stimulus (Harris & MacFarlane, 1974). Furthermore, infants demonstrate longer latencies to localize peripheral stimuli if a central stimulus is present (Aslin & Salapatek, 1975). These findings have been interpreted as an effect of attention to the central stimulus (Harris & MacFarlane, 1974; Finaly & Ivinskis, 1984; Richards, 1987). A lack of responsiveness to a peripheral stimulus is indicative of an enhanced level of attention directed toward the central stimulus, and responsiveness to a peripheral stimulus indicates distractibility due to a lack of attention toward the central stimulus.

Several studies have used the HR-defined attention phases to study infant distractibility (Casey & Richards, 1988; Hicks & Richards, 1998; Hunter & Richards, 2003; Lansink & Richards, 1997; Richards, 1987, 1997b; Richards & Hunter, 1997; Richards & Turner, 2001; see review in Richards & Lansink, 1998). These studies have several things in common. First, the infants attention is attracted to a central stimulus. This center stimulus has been computer-generated visual patterns, audiovisual patterns, movies and television programs such as "Sesame Street", and objects and small toys. Second, HR is recorded during the presentations and computer algorithms evaluate the HR online. When a significant deceleration in HR occurs, or when HR returns to its prestimulus level, a stimulus is presented in the periphery. The peripheral stimuli have been small lights, a presentation of a large stimulus on another television, a small peripheral square, or dynamic stimulus presented in the periphery. Third, a consistent finding has been found in each of these studies. When a peripheral stimulus is presented contingent upon the deceleration of HR, i.e., sustained attention is occurring, a localization to the peripheral stimulus does not occur, or takes a long time. Alternatively, when the peripheral stimulus is presented contingent upon the return of HR to its prestimulus level, i.e., attention termination, peripheral stimulus localization occurs more frequently and rapidly. These findings imply that it is not simply the presence of a central stimulus that attenuates peripheral stimulus localization. Rather, increased attentiveness to the central stimulus blocks or attenuates the localization of the peripheral stimulus. If the infant is looking at the central stimulus but not attentive, peripheral stimulus occurs at nearly normal levels (see Richards & Lansink, 1998, for further details).

An example of these studies is that of Richards (1997b). This study examined the impact of infant attention to a central stimulus on peripheral stimulus localization. A cross-sectional design was utilized with infants of 14, 20, and 26 weeks of age. Infants were seated in a parent's lap facing the inner edges of two TV monitors. A central stimulus (computer generated patterns or a sesame street program) was presented on one monitor and a peripheral stimulus (a white square traveling from top to bottom) was presented on the other monitor. The onset of peripheral stimulus presentations was determined online by HR changes or by predetermined time delays. The heart-rate-defined delays were: HR deceleration, HR deceleration plus 2 seconds, HR acceleration, and HR acceleration plus 2 seconds. The HR deceleration delays represented periods in which the infant was engaged in sustained attention and the HR acceleration delays represented attention termination. The time-defined delays were 0, 2, 4, 6, 8, 10, and 12 seconds. For the time-defined delays, the level of HR change at the onset of the peripheral stimulus was measured.

Figure 8 shows the percentages of peripheral stimulus localization as a function of the HR changes occurring during the presentations. The detection of the peripheral stimulus when no central stimulus was present (Prestim in Figure 8) was about 80%, and was close to that when the HR had returned to its prestimulus level (HRAcc in Figure 8; attention termination). Conversely, shortly after stimulus presentation (Immed in Figure 8) or during HR deceleration (HRDec; sustained attention) peripheral stimulus localization dropped to about 35%. The small levels of peripheral stimulus localization during sustained attention indicate an enhanced level of attention directed toward the central stimulus. The increased levels of responding to the peripheral stimulus in the prestimulus or attention termination periods indicates inattentiveness toward the central stimulus.

In addition to measuring the percentage of peripheral stimulus localizations following these delays, the epochs of peripheral stimulus localization trials were classified into four categories for signal detection analysis: localization (hit), nonlocalization (miss), correct rejection, and false alarm (also see Hicks & Richards, 1998). The latter two categories applied to control trials in which no peripheral stimulus was presented. The purpose of this analysis was to determine whether attention affected stimulus discriminability or response bias. The results of the signal detection analysis provide insight into a possible mechanism behind the impact of attention on peripheral stimulus localization. Stimulus discriminabilty was equivalent for the sustained attention and attention termination epochs, but localization was more probable during attention termination than sustained attention. In addition, the false alarm percentage during attention termination was significantly higher than during sustained attention indicating a low response bias against responding to the peripheral stimulus during periods of inattention. The bias against responding to the peripheral stimulus was much higher during sustained attention. These findings demonstrate that the effect of attention on peripheral stimulus localization is due to an increased bias to maintain fixation toward the central stimulus during sustained attention. Attentional processes do not affect perceptual sensitivity toward peripheral distractors, instead infant-controlled decision processes to maintain attention toward the central stimulus explain lower percentages of peripheral stimulus localization during sustained attention.

Attention and Recognition Memory

Another construct of interest to developmental psychophysiologists is recognition memory. The paired-comparison procedure is a behavioral measure often utilized in recognition memory studies. This procedure entails familiarizing the infant with an individual visual stimulus. Following the familiarization procedure, the infant is simultaneously presented with two stimuli. One stimulus is the previously seen familiar stimulus; the other stimulus is a novel stimulus. Look duration toward each stimulus is the dependent variable. A novelty preference is indicative of recognition of the familiar stimulus because infants naturally prefer to look at novel stimuli. A familiarity preference indicates partial processing of the previously seen stimulus during the familiarization phase (Hunter, Ross, & Ames, 1982; Rose, Gottfried, Melloy-Carminar, & Bridger, 1982; Wagner & Sakovits, 1986). Past research indicates that older infants require less exposure time during the familiarization phase than younger infants to demonstrate a novelty preference (Colombo, Mitchell, & Horowitz, 1988; Rose, 1983; Rose et al., 1982). Rose et al. (1992) found that 3- and 6-month-olds demonstrated familiarity preferences following familiarization exposure times of 5 or 10 seconds. Three-month-olds required 30 seconds of familiarization to demonstrate novelty preferences, while 6-month-olds required only 15 seconds of familiarization. It is clear that older infants process the familiar stimulus more efficiently than younger infants. One possible explanation for this age effect is that older infants are more attentive during familiarization than younger infants.

Richards (1997a) investigated the role of attention in the paired-comparison recognition memory paradigm. Infants 14, 20, and 26 weeks of age were shown a Sesame Street video in order to elicit the various phases of attention. After a delay, infants were exposed to a visual pattern for 2.5 or 5 seconds. The visual pattern was presented while the infant was engaged in sustained attention, attention termination, or 5 seconds following attention termination. It was hypothesized that each of these conditions would be associated with differential amounts of processing of the familiar stimulus. Exposure during sustained attention should be associated with enhanced processing compared to exposure during attention termination. The last condition was used because

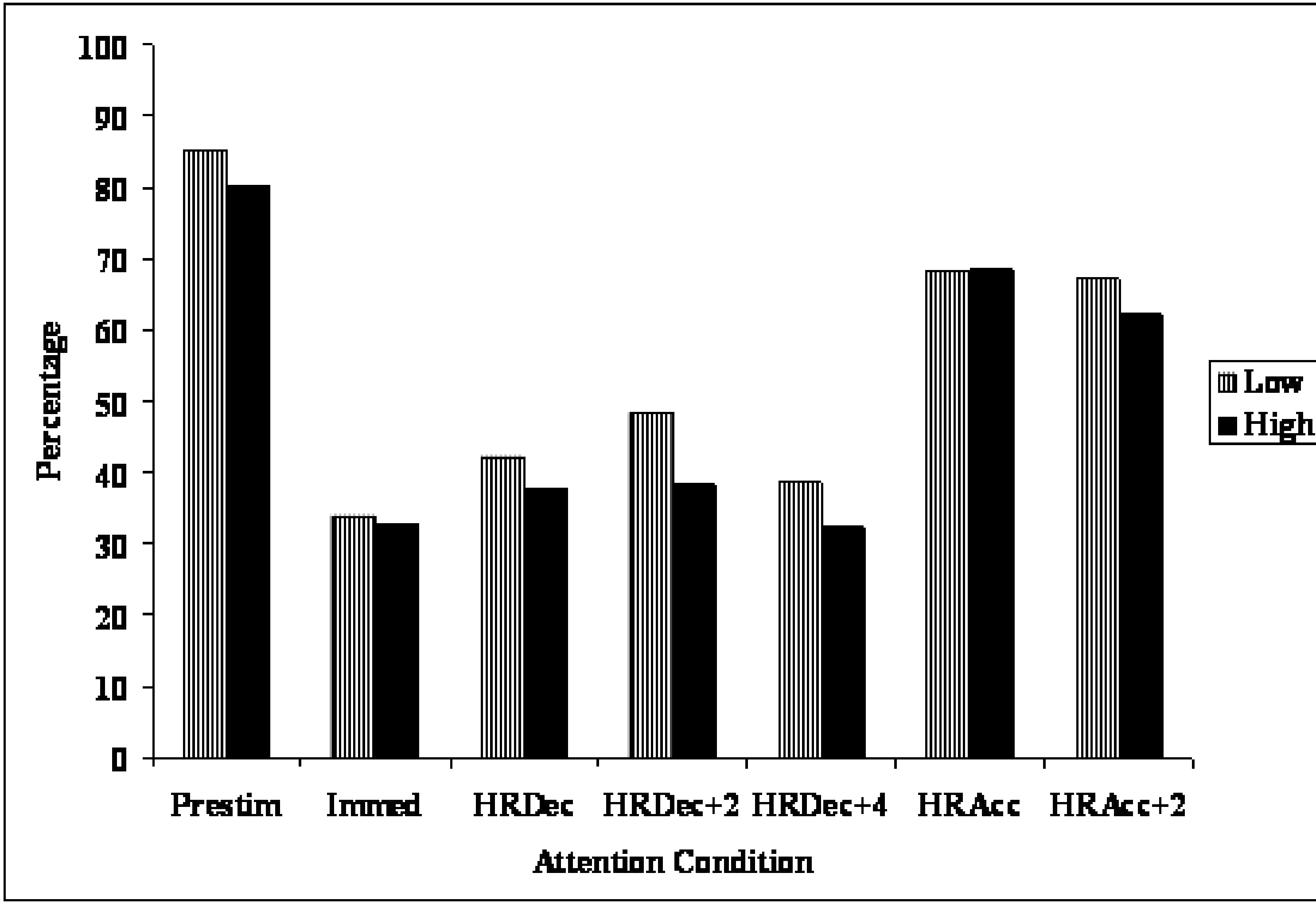

Figure 8: Percentages of peripheral stimulus localization as a function of the HR changes occurring during distractor presentations. No central stimulus was present during the prestimulus period (Prestim). The immediate period (Immed) refers to stimulus onset. Sustained attention coincides with all of the HR deceleration periods (HRDec), and attention termination is represented by HR accelerations (HRAcc). (adapted from Richards, 1997b)

following the process of attention termination infants should be receptive to the presentation of a novel stimulus.

In contrast to Rose and colleagues' (1982) finding that 6-month-olds require 15 seconds of exposure to demonstrate a novelty preference, in the sustained attention and the attention termination plus 5 seconds delay conditions, 20- and 26-week-olds (i.e., 4.5- and 6-month-olds) preferred the novel stimulus after only 5 seconds of familiarization. These age groups demonstrated familiarity preferences with 5 seconds of familiarization during the attention termination delay condition. Moreover, a post-hoc analysis of the attention termination plus 5 seconds delay condition revealed that exposure to the familiarization phase during sustained attention was positively correlated with novelty preferences during the test phase. This indicates that infants demonstrating a novelty preference in this condition had cycled out of attention termination and were once again engaged in sustained attention. Thus, determining stimulus presentation based on visual fixation and HR measures of attention provides greater control over the attentional status of the infant during exposure and may lead to an increased effect size than when stimulus presentation is based upon visual fixation alone.

Individual differences in look duration and the amount of time spent in various HR phases of attention related to performance in the paired comparison paradigm has been investigated (Colombo, Richman, Shaddy, Greenhoot, & Maikranz, 2001). Longer duration of looking during a pretest phase and the familiarization phase were positively associated with more time spent in sustained attention and attention termination. Interestingly, individual differences in the overall amount of time spent in sustained attention did not account for a significant amount of variance in recognition memory performance, but individual differences in attention termination did account for a significant amount of variance in performance. However, amount of time spent in attention termination was negatively correlated with novelty preferences. The greater the amount of time spent in attention termination the less likely the infant was to demonstrate a novelty preference.

Several studies of infant recognition memory development have used the electroencephalogram (EEG) to measure event-related potentials (ERPs) related to recognition memory. ERPs are voltage oscillations recorded on the scalp that are time-locked with a specific physical or mental event (Fabiani, Gratton, & Coles, 2000; Picton, Bentin, Berg, Donchin, Hillyard, Johnson, Miller, Ritter, Ruchkin, Rugg, & Taylor, 2000). Nelson and Collins (1991,1992) designed a modified oddball procedure for measuring ERP correlates of recognition memory in infants. First, infants are exposed to repeated presentations of two different stimuli. Then, the participants are exposed to one of the familiar stimuli on 60% of the trials (frequent familiar), the other familiar stimulus on 20% of the trials (infrequent familiar), and novel stimulus presentations on the remaining 20% of the trials (infrequent novel). Infants tested using the modified oddball procedure demonstrate a large negative ERP component occurring about 400-800 ms after stimulus onset located primarily in the frontal and central EEG leads. This has been labeled the "Negative central" (Nc) component (Courchesne, 1977, 1978). Nelson and Collins (1991, 1992) found no differences between the Nc component for any of the stimulus presentation conditions for 4-, 6-, and 8-month-old infants. The authors concluded that the Nc is indicative of a general orienting response. Later components of the ERP did differ between presentation conditions for older infants. Thus, it is plausible that the late slow wave ERP components reflect processes associated with recognition memory while the Nc component reflects general orienting and attention.

The close association of attention and the Nc component was addressed in a study by Richards (2003). Infants were tested at 4.5, 6, or 7.5 months of age. During the modified oddball procedure, a recording of Sesame Street was presented between the brief stimulus presentations. Heart rate changes elicited by the Sesame Street presentation were used to distinguish periods of time before attention was engaged (before heart rate deceleration), during sustained attentiveness (during heart rate deceleration), and inattentiveness after sustained attention (after heart rate deceleration). The ERP components occuring during sustained attention were compared to those occurring during periods of inattentiveness. There were several findings of interest. First, the Nc did not differ for the three stimulus types (frequent familiar, infrequent familiar, infrequent novel), but the Nc amplitude was significantly larger during periods of attention (i.e., stimulus orienting and sustained attention) than during periods of inattentiveness (see Figure 9). The Nc component during sustained attention also increased in amplitude with

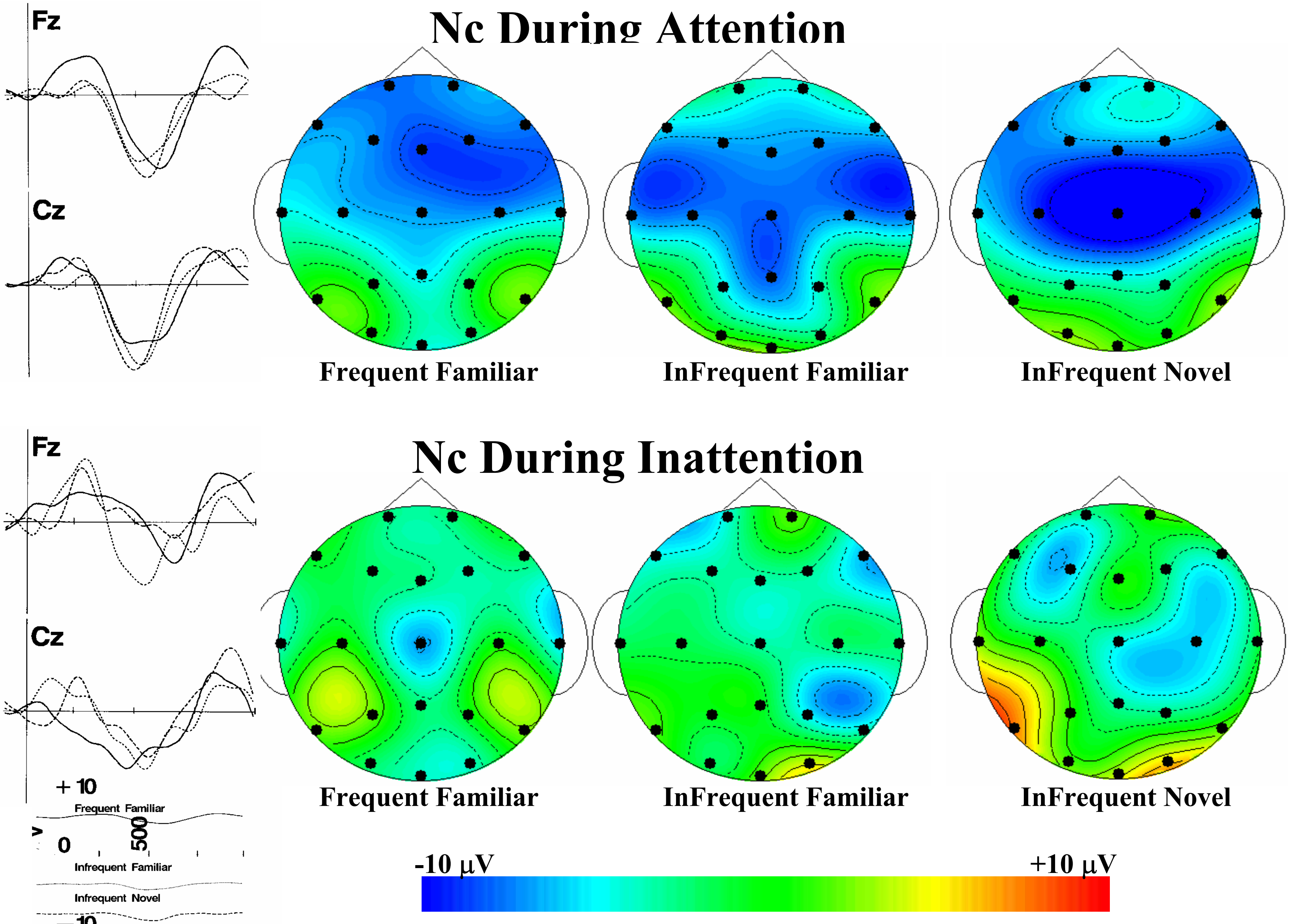

Figure 9: The Nc component during attention and inattention. The ERP recording from 100 ms prior to stimulus onset through 1 s following stimulus onset is shown for the Fz and Cz electrodes for attentive (top figures) and inattentive (bottom figures) periods, combined over the three testing ages. The topographical scalp potential maps show the distribution of this component for the three memory stimulus types in attention and inattention. The topographical maps represent an 80-ms average of the ERP for the Nc component at the maximum point of the ERP response. The data are plotted with a cubic spline interpolation algorithm and represent absolute amplitude of the ERP (Richards, 2003).

age. Second, late slow waves were found at about 1 to 2 s following stimulus onset that were primarily negative and found across all electrodes. While attentive, 4.5-month-olds demonstrated a positive late slow wave that was similar for familiar and novel presentations. The older infants (6- and 7.5-month-olds) displayed a negative late slow wave following presentations of the novel stimulus that stood in contrast to the positive slow wave these groups displayed following infrequent familiar stimulus presentations. The positive slow wave is likely a response associated with an updating of working memory following presentation of a familiar yet only partially encoded stimulus, whereas the negative slow wave represents the initial processing of new information provided by a novel stimulus. The age differences suggest that (during sustained attention) the older two ages were sensitive to stimulus novelty and probability, whereas the younger infants were sensitive only to stimulus probability. The stimulus presentations occurring during inattention did not show the slow wave differences between the three presentation procedures.

We are currently (Reynolds & Richards, 2003) conducting an investigation of the relationship between attention and ERP correlates of recognition memory in infants utilizing high-density (124 channel) EEG recordings and HR. The studies discussed in the preceding paragraphs utilized small numbers of electrodes when recording EEG (< 30). The data obtained using relatively small numbers of electrodes can only yield limited conclusions regarding the electrical activity measured at the scalp, and cannot be used to accurately estimate the cortical sources of this electrical activity. High-density EEG recordings provide sufficient data for estimating the cortical sources of ERP components. Equivalent current dipole analysis is used to determine source localization (Richards & Hunter, 2002). Preliminary findings indicate that the cortical source of the Nc component is in areas of frontal cortex including the anterior cingulate. The anterior cingulate is part of the cingulate cortex – a paralimbic region of the brain that shares reciprocal connections with several subcortical, cortical, and limbic regions (Cohen, 1993). Studies have shown that the anterior cingulate is involved in visual target detection, and the control or direction of attention (Casey, Trainor, Giedd, Vauss, Vaituzis, Hamburger, Kozuch, & Rapoport, 1997; Goldman-Rakic, 1988). The Nc component was greater in magnitude during sustained attention than during periods of inattention (replicating Richards, 2003). Additionally, infants demonstrated Nc of greater magnitude following novel stimulus presentations than familiar stimulus presentations. This effect was only found when infants were engaged in sustained attention. The interaction between HR attention phases and stimulus type on the magnitude of the Nc component combined with cortical source localization of Nc in the anterior cingulate suggests that the Nc component represents a general orienting response more closely associated with attention than with recognition memory (Nelson & Collins, 1991, 1992; Richards, 2003). Moreover, the use of HR as a means of controlling for attentiveness during stimulus presentation may serve to increase effect sizes found in studies utilizing EEG recordings (similar to increased effect sizes found in behavioral studies).

Heart Rate Variability

Resting HR shows variability in normal, healthy humans. The pacemaker cells in the SA node spontaneously depolarize at a constant rate. Thus, left unaided, resting HR would be a continuous unvarying level. However, several sources of variability occur in HR due to the central and autonomic nervous systems. Blood pressure regulation, homeostatic control for activity needs, and respiration all act to modify the pacemaker cells depolarization, and thus keep resting HR variable. Thus, variability in HR is assumed to reflect continuous feedback between the central nervous system and peripheral autonomic receptors.

A well-known variability in HR is called “respiratory sinus arrhythmia” (RSA) Variability in HR has been found to oscillate at three frequencies (Berntson, Bigger, Eckberg, Grossman, Kaufmann,Malik, Nagaraja, Porges, Saul, Stone, & van-der-Molen, 1997; Porges, 1992; Porter, 2001). The highest frequency oscillation in HR ranges from 0.3 to 1.5 Hz. Accelerations and decelerations in HR occurring in this frequency band occur at the same rate of respiration inhalations and exhalations (Porter, Bryan, & Hsu, 1995; Richards & Casey, 1992), thus giving the term “respiratory” to RSA. As presented in the first section, the brain areas controlling RSA are well-known. This rhythmic activity is controlled by brain stem respiratory centers modulating the parasympathetic influence over HR via the vagus nerve. Because of its close association with the level of vagal activity, RSA is often labeled "vagal tone" (Porges, 2001).

Porges (1985, 1992; Porges & Bohrer, 1991) has developed a method for quantifying RSA . This method involves four steps: (1) detection of the IBIs, (2) time sampling of the heart period data, (3) detrending the heart period time series with the use of a moving band-pass filter, and (4) extracting and logarithmically transforming the variance in the frequency band associated with respiration. Other methods of obtaining variability measures at the frequency of RSA include spectral analysis and peak-to-trough filters (Askelrod, Gordon, Madwed, & Snidman, Shannon, & Cohen, 1985; Berntson et al., 1997; Scalabassi, & Estrin,1976; Richards, 1986; Womack, 1971; Schechtman, Kluge, & Harper, 1981). Richards (1995b) has evaluated the reliability of RSA for each method of quantification in infants and found that the use of moving band-pass filters is more reliable in some cases than peak-to-trough filters, additionally spectral analysis techniques require longer sampling durations to demonstrate reliability than the other methods. Furthermore, utilizing a fixed high-frequency band corresponding to RSA frequency (.333 –1.250 Hz) produced results equivalent to those found using the observed respiration frequency found from measuring actual respiration with a pneumatic chest cuff. This indicates that the measurement of HR along with filtering techniques is adequate for the measurement of RSA in infants, and measuring the actual respiration of infants to determine their specific respiration frequency is not necessary for obtaining reliable, valid data.

Infant Heart Rate Variability Studies

Many studies have shown a relationship between resting levels of HR variability, particularly RSA, and infant attention and social behavior. Individual differences in HR responding are shown by the strong relation between changes in sustained attention and RSA in early development. Heart rate change during sustained attention increases from 8 weeks to 6 months of age (Richards, 1985; see Table 1a). From 3 to 6 months of age, the HR response during sustained attention is larger for infants with high levels of RSA than those with low RSA (Table 1b). Overall, RSA is stable over this age range (Izard et al., 1991; Richards, 1989, 1994). The relation between RSA and sustained attention appears to be due to developmental change in RSA during this time period (Table 1c). RSA increases over the first year of life and HR decreases (Bar-Haim, et al., 2000; Frick & Richards, 2001; Harper et al., 1978; Katona, Frasz, & Egbert, 1980; Richards, 1985b, 1987; Richards & Casey, 1991; Watanabe, Iwase, & Hara, 1973). Increases in RSA most likely account for developmental decreases in resting HR and increases in HR responding during sustained attention.

The reason that HR changes during attention and RSA are correlated is likely due to their common control by the parasympathetic nervous system. The HR deceleration occurring during attention, indicating the onset of stimulus orienting and sustained attention, is caused by a large efferent discharge of vagal activity. Similarly, the rhythmic aspect of RSA is controlled by the brainstem respiratory centers, but the changes in HR are mediated by the vagal innervation of the heart. The relation between these two systems suggests that individual differences in RSA level do reflect a tonic difference in resting vagal activity (i.e., vagal tone; Porges, 2001). Thus, heart rate variability manifested in vagal tone (RSA level) is correlated with sustained attention because both are mediated through activity of the same network of structures within the central nervous system.

Table 1. (A) Heart rate changes in attention phases from 2 to 6 months of age. (B) Heart rate changes in attention phases for high and low RSA infants. (C) Baseline HR and RSA in full-term infants from 3 to 6 months of age (adapted from Richards, 1995a).

1A. Heart rate changes in attention phases from 2 to 6 months				
	8 weeks	14 weeks	20 weeks	26 weeks
Stimulus orienting	-3.7	-4.2	-5.2	-4.7
Sustained attention	-6.9	-6.9	-8.5	-11.0
Attention termination	-1.7	-2.8	0.3	0.3

1B. Heart rate changes in attention phases for high and low RSA infants		
	Low RSA	High RSA
Stimulus orienting	-4.8	-5.2
Sustained attention	-7.9	-11.5
Attention termination	-1.3	-0.5

1C. Baseline HR and RSA in full-term infants from 3 to 6 months of age			
	14 weeks	20 weeks	26 weeks
Baseline HR	152	148	142
Baseline RSA	0.78	0.86	0.92

Other measures of HR variability during testing have been found to be related to individual differences in looking time in the visual habituation paradigm (Maikranz, Colombo, Richman, & Frick, 2000). In the visual habituation paradigm, infants receive multiple exposures to a visual stimulus. The duration of looks toward the stimulus decline across repeated presentations as the stimulus is more fully processed. Look duration is measured as an indicator of attention and information processing during habituation. The duration of looks reflects the efficiency of information processing in individual infants (Cohen, 1988; Colombo & Mitchell, 1990). Look duration is moderately stable across the first year of postnatal life and may reflect individual differences in cognitive functioning (Bornstein, Pecheaux, & Lecuyter, 1988; Byrne, Clark-Tousenard, Hondas, & Smith, 1985; Colombo, 1993; Colombo & Mitchell, 1990). From this perspective, infants demonstrating shorter look durations (short-lookers) during habituation are posited as more efficient information processors than infants demonstrating longer look durations (long-lookers). In support of this hypothesis, short-looking infants achieve novelty preferences in the paired-comparison paradigm with comparatively shorter familiarization exposure times than long-looking infants (Colombo, Freeseman, Coldren, & Frick, 1995; Colombo, Mitchell, Coldren, & Freeseman, 1991; Frick & Colombo, 1996; Jankowski & Rose, 1997). Maikranz et al. (2000) found that at 4 months of age, short-looking infants demonstrate greater HR variability than long-looking infants across habituation sessions. Additionally, long-looking infants displayed greater acceleration in HR following stimulus onsets than short-looking infants. This may indicate that long-looking infants are more physiologically reactive during testing procedures than short-looking infants, thus the long-lookers may have actually reacted with a startle response to stimulus onsets. In a study conducted by Bornstein and Suess (2000), infants with higher baseline RSA at 2 and 5 months of age demonstrated shorter looking times in an infant-controlled habituation task than lower baseline RSA infants. Greater suppression of RSA during habituation was associated with more efficient habituation. Richards and Casey (1991) found that RSA decreases during sustained attention. Thus, infants demonstrating suppression of RSA during habituation were likely engaged in sustained attention.

Frick and Richards (2001) investigated the relationship between baseline RSA, attention, and performance on the paired-comparison paradigm in 14-, 20-, and 26-week-olds. Baseline RSA was measured followed by administration of the paired-comparison procedure with familiarization exposure presented during periods of attention or inattention as indicated by HR phases. Older infants (i.e., 20- and 26-week-olds) and infants with higher RSA showed more evidence of recognition memory than the 14-week-olds and the low RSA infants. Additionally, familiarization exposure during sustained attention was associated with greater novelty preferences than familiarization exposure during periods when HR indicated inattention (replicating Richards, 1997a). Infants from 14 to 26 weeks of age with high baseline RSA have larger and more sustained HR responses in sustained attention than do low RSA infants (Casey & Richards, 1988; Richards, 1985, 1987, 1989). Heart rate changes in sustained attention correlate with RSA, whereas rate changes in stimulus orienting and attention termination do not correlate with RSA (Richards, 1985).

Variability in HR has been found to correlate with behavioral measures of temperament. In particular, behavioral inhibition is a personality style associated with temperament in which the child is reluctant to display approach behaviors in unfamiliar conditions. High RSA is associated with behavioral inhibition in children across cultures (e.g., Kagan, Kearsley, & Zelazo, 1978; Garcia-Koll, Kagan, & Reznick, 1984). RSA is associated with individual differences in attention, thus it is not surprising that long-term differences in performance on behavioral measures of temperament correlate with RSA. However, it is interesting that high RSA (associated with greater attentional functioning) is associated with behavioral inhibition. Kagan has posited that this finding may be due to a decrease in RSA associated with increased mental work load for behaviorally inhibited children in unfamiliar situations. This significant increase in processing of information in unfamiliar situations may not occur in uninhibited children.

Research conducted by Fox (1989) indicates that greater RSA in the first year of life is associated with greater cardiovascular and behavioral reactivity to environmental stimulation. Infants with higher RSA at birth demonstrate more self-regulatory behaviors in response to arm restraint at 5 months. Five-month-olds with high RSA also display more negative expressions during arm restraint than low RSA infants (Stifter & Fox, 1990). Additionally, infants with greater RSA demonstrate longer durations of interest expression in face-to-face interactions with their mothers (Fox & Gelles, 1984). Feldman, Greenbaum, & Yirmiya (1999) noted that face-to-face interactions begin around 2 months of age, and they expose the infant to high levels of cognitive and social information. The coordination of affective expressions (termed mother-infant affect synchrony) during face-to-face interactions is believed to facilitate transition from mutual-regulation to self-regulation. Self-regulation develops in the context of mutual regulation between parent and infant. Maternal-infant affect synchrony at 3 months of age is negatively correlated with infant negative affect during maternal-infant interactions. Maternal-infant affect synchrony in interaction at 3 months of age is positively related to self-control at 9 months of age, and both are negatively correlated with difficult temperament. Thus, although high RSA is associated with behavioral inhibition, infants with high RSA may be more responsive during maternal-infant interactions associated with the development of enhanced self-regulatory capacities. Thus, depending on early social experience with a primary caregiver, infants with high RSA may or may not develop behaviors consistent with maladaptive temperament categories (e.g., behavioral inhibition). The relationship between RSA and temperament measures is not clear at this point and may change over time with development.

Summary and Conclusion

The use of the HR in developmental psychophysiological research has been reviewed in three ways. These ways are HR changes, phases of attention indexed by HR, and HR variability. The research in this area has provided valuable insight into cognitive functioning in infants before they are able to provide verbal responses or engage in complex behavioral tasks. These HR measures are all associated with activity in similar and dissimilar brain areas. A common brain area for HR change is the sympathetic or parasympathetic innervation of the heart, since all CNS control influences HR via these systems. However, phasic HR changes during stimulus orienting, the extended slowing of HR during sustained attention, and the rhythmic variability found in RSA, are controlled by different brain systems. We believe that the research with infants using HR not only has provided an interesting set of findings concerning infants' psychological processes, but an understanding of the cognitive neuroscience processes influencing such behaviors.

Developmental change has been documented in HR responses throughout the first year of postnatal life. For example, resting HR decreases (Bar-Haim et al., 2000; Izard et al., 1991), and HR responses to stimulus presentations change in direction and/or magnitude with age during infancy (e.g., Berg, 1975; Berg & Berg, 1979; Graham, et al., 1970; Graham et al., 1983; Harper et al., 1976, 1978; Katona et al., 1980; Watanabe et al., 1973). The level of HR change during sustained attention increases from 8 to 26 weeks of age. This change in sustained attention parallels an increasing ability of infants to acquire familiarity with stimulus characteristics in a fixed length of time (e.g., Frick & Richards, 2001; Richards, 1997a). This occurs primarily during sustained attention, rather than the other attention phases. Sustained attention is the HR phase indicative of intensive cognitive processing. RSA increases during this time period and this increase most likely accounts for the developmental changes found in sustained attention (Bar-Haim et al., 2000; Frick & Richards, 2001; Harper et al., 1978; Katona et al., 1980; Richards, 1985b, 1987; Richards & Casey, 1991; Watanabe et al., 1973).

Changes in RSA and sustained attention reflect further development of a "general arousal attention system" composed of reciprocal connections in the frontal cortex, the limbic system, and the mesencephalic reticular activating system (Heilman et al., 1987; Mesulam, 1983; Richards, 2001; Richards & Casey, 1992; Richards & Hunter, 1998). Developmental changes in sustained attention and RSA throughout infancy are a result of this system developing, the development of this system's role in invigorating neural systems involved in attention, and the increasing level of integration between this general arousal system and attention systems that specifically enhance cognitive operations. Sustained attention thus correlates with behavioral measures of attention and information processing. High RSA infants demonstrate greater HR responses during sustained attention (Richards, 1995a). Baseline measures of RSA are indicative of individual differences in the capacity of infants to demonstrate sustained attention. Heart rate measures can thus be used as an immediate measure of cognitive processing in infants, and as a measure of an individual infant's capacity to demonstrate attentional responses necessary for thorough information processing. This provides developmental psychophysiologists with an invaluable tool for investigating cognitive development in infancy.

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References

Akselrod, S., Gordon, D., Madwed, J.B., Snidman, N.C., Shannon, D.C., & Cohen, R.J. (1985). Hemodynamic regulation: Investigation by spectral analysis. American Journal of Physiology, 249, H867-H875.

Andreassi, J.L,. (1989). Psychophysiology: Human behavior and physiological response. Hillsdale, NJ: Erlbaum.

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.

Aslin, R.N., & Salapatek, P. (1975). Saccadic localization of visual targets by the very young human infant. Perception and Psychophysics, 17, 293-302.

Atkinson, J., Hood, B., Braddick, O.J., & Wattam-Bell, J. (1988). Infants' control of fixation shifts with single and competing targets: Mechanisms for shifting attention. Perception, 17, 367-368.

Atkinson, J., Hood, B., Wattam-Bell, J., & Braddick, O.J. (1992). Changes in infants' ability to switch visual attention in the first three months of life. Perception, 21, 643-653.

Bar-Haim, Y., Marshall, P.J., & Fox, N.A. (2000). Developmental changes in heart period and high-frequency heart period variability from 4 months to 4 years of age. Developmental Psychobiology, 37, 44-56.

Bell, M.A. (1998). In J.E. Richards (Ed.), Cognitive neuroscience of attention: A developmental perspective (pp. 287-316). Hillsdale, NJ: Lawrence Erlbaum Press.

Berg, W.K. (1975). Cardiac components of the defense response in infants. Psychophysiology, 12, 244 (abstract).

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: Wiley.

Berntson, G.G., Bigger, J.T., Eckberg, D.L., Grossman, P., Kaufmann, P.G., Malik, M., Nagaraja, H.N., Porges, S.W., Saul, J.P., Stone, P.H., van der Molen, M.W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. Psychophysiology, 34, 623-648.

Berntson, G.G., Cacioppo, J.T., Quigley, K.S. (1993). Respiratory sinus arrhythmia: Autonomic origins, physiological mechanisms, and psychophysiological implications. Psychophysiology, 30, 183-196.

Bornstein, M.H., Pecheux, M.G., & Lecuyer, R. (1988). Visual habituation in human infants: Development and rearing circumstances. Psychological Research, 50, 130-133.

Bornstein, M.H., & Suess, P.E. (2000). Physiological self-regulation and information processing in infancy: Cardiac vagal tone and habituation. Child Development, 71, 273-287.

Brown, J.W., Leavitt, L.A., & Graham, F.K. (1977). Response to auditory stimuli in 12-week-old infants. Developmental Psychobiology, 10, 255-266.

Brownley, K.A., Hurwitz, B.E., & Schneiderman, N. (2000). Cardiovascular psychophysiology. In J.T. Cacioppo, L.G. Tassinary, & G.G. Berntson (Eds.), Handbook of psychophysiology (pp. 224-264). Cambridge, UK: Cambridge University Press.

Byrne, J.M., Clark-Tousenard, M.E., Hondas, B.J., & Smith, I.M. (1985). Stability of individual differences in infant visual attention. Unpublished paper presented at the Biennial Meeting of the Society for Research in Child Development, Toronto, Canada.

Casey, B.J., & Richards, J.E. (1988). Sustained visual attention measured with an adapted version of the visual preference paradigm. Child Development, 59, 1514-1521.

Casey, B. J., & Richards, J. E. (1991). A refractory period for the heart rate response in infant visual attention. Developmental Psychobiology, 24, 327-340.

Casey, B.J., Trainor, R., Giedd, J., Vauss, Y., Vaituzis, C.K., Hamburger, S., Kozuch, P., & Rapoport, J.L. (1997). The role of anterior cingulated in automatic and controlled processes: A developmental neuroanatomical study. Developmental Psychobiology, 30, 61-69.

Chase, H.H. (1965). Habituation of an acceleratory cardiac response in neonates. Unpublished Master's thesis, Unversity of Wisconsin.

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

Clifton, R.K., & Nelson, M.N. (1976). Developmental study of habituation in infants: The importance of paradigm, response system and state. In T.J Tighe & R.N. Leaton (Eds.), Habituation: Perspectives from child development, animal behavior, and neurophysiology (pp. 159-206), Hillsdale, NJ: Erlbaum.

Cohen, L.B. (1988). The relationship between infant habituation and infant information processing. European Bulletin of Cognitive Psychology/Cahiers de Psychologie Cognitive, 8, 442-444.

Cohen, R.A. (1993). The neuropsychology of attention. New York, NY: Plenum Press.

Colombo, J. (1993). Infant cognition: Predicting later intellectual functioning. Newbury Park, CA: Sage Production, Inc.

Colombo, J., Freeseman, L.J., Coldren, J.T., & Frick, J.E. (1995). Individual differences in infant visual fixation: Dominance of global and local stimulus properties. Cognitive Development, 10, 271-285.

Colombo, J., & Mitchell, D.W. (1990). Individual and developmental differences in infant visual attention. In J. Colombo & J.W. Fagan (Eds.), Individual differences in infancy (pp. 193-227). Hillsdale, NJ: Erlbaum.

Colombo, J., Mitchell, D.W., Coldren, J.T., & Freeseman, L.J. (1991). Individual differences in infant visual attention: Are short lookers faster processors or feature processors? Child Development, 62, 1247-1257.

Colombo, J., Mitchell, D.W., & Horowitz, F.D. (1988). Infant visual behavior in the paired- comparison paradigm. Child Development, 59, 1198-1210.

Colombo, J., Richman, W.A., Shaddy, D.J., Greenhoot, A.F., & Maikranz, J.M. (2001). Heart rate-defiend phases of attention, look duration, and infant performance in the paired-comparison paradigm. Child Development, 72, 1605-1616.

Courchesne, E. (1977). Event-related brain potentials: Comparison between children and adults. Science, 197, 589-592.

Courchesne, E. (1978). Neurophysiological correlates of cognitive development: Changes in long-latency event-related potentials from childhood to adulthood. Electroencephalography and Clinical Neurophysiology, 45, 468-482.

Darrow, C.W. (1929). Differences in the physiological reactions to sensory and ideational stimuli. Psychological Bulletin, 26, 185-201.

Davis, R.C., Buchwald, A.M., & Frankmann, R.W. (1955). Autonomic and muscular responses and their relation to simple stimuli. Psychological Monographs, 69, 1-71.

Davis, C. M., Crowell, D.H., & Chun, B.J. (1965) Monophasic heart rate accelerations in human infants to peripheral stimulation. American Psychologist, 20, 478 (Abstract)

de Schonen, S., McKenzie, B., Maury, L., & Bresson, F. (1978). Central and peripheral object distances as determinants of the effective visual field in early infancy. Perception, 7, 499-506.

Diamond, A., Cruttenden, L., & Neiderman, D. (1994). AB with multiple wells: 1. Why are multiple wells sometimes easier than two wells? 2. Memory or memory + inhibition. Developmental Psychology, 30, 192-205.

Diamond, A., Prevor, M.B., Callender, G. & Druin, D.P. (1997). Prefrontal cortex cognitive deficits in children treated early and continuously for PKU. Monographs of the Society for Research in Child Development, 62 (4, Serial No. 252).

Einthoven, W., Fahr, G., & de Waart, A. (1913). Uber die richtung und die manifeste grosse der pontetialshwankungen in menchlichen herzen und uber den einfluss der herzlage auf die for des elecktrokardiogram. Archives of Physiology, 150, 275-315.

Fabiani, M., Gratton, G., & Coles, M.G.H. (2000). Event-related brain potentials: Methods, theory, and applications. In J.T. Cacioppo, L.G. Tassinary, & G.G. Berntson (Eds.), Handbook of psychophysiology (pp. 53-84). New York, NY: Cambridge University Press.

Feldman, R., Greenbaum, C.W., & Yirmiya, N. (1999). Mother-infant affect synchrony as an antecedent of the emergence of self-control. Developmental Psychology, 35, 223-231.

Field, J., Muir, D., Pilon, R., Sinclair, M., & Dodwell, P. (1980). Infants' orientation to lateral sounds from birth to three months. Child Development, 51, 295-298.

Finlay, D., & Ivinskis, A. (1984). Cardiac and visual responses to moving stimuli presented either successively or simultaneously to the central and peripheral visual fields in 4-month-old infants. Developmental Psychology, 20, 29-36.

Fox, N.A. (1979). Cardiac responses to two types of auditory stimuli in preterm infants. Unpublished paper presented at the annual meeting of the Society for Psychophysiological Research, Cincinnati, Ohio.

Fox, N.A. (1989). Psychophysiological correlates of emotional reactivity during the first year of life. Developmental Psychology, 25, 364-372.

Fox, N.A., & Gelles, M. (1984). Face-to-face interaction in term and preterm infants. Infant Mental Health Journal, 5, 192-205.

Frick, J.E., & Colombo, J. (1996). Individual differences in infant visual attention: Recogntion of degraded visual forms by 4-month-olds. Child Development, 67, 188-204.

Frick, J.E., & Richards, J.E. (2001). Individual differences in recogntion of briefly presented stimuli. Infancy, 2, 331-352.

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

Goldman-Rakic, P.S. (1988). Topography of cognition: Parallel distributed networks in primate association cortex. Annual Review of Neuroscience, 11, 137-156.

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, N.J.: Erlbaum.

Graham, F.K., Anthony, B.J., & Ziegler, 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 (Vol 5, pp. 59-17), New York: Academic 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. (1976). Time series analysis and sleep research. IEEE Transactions and Autonomic Control, AC-19, 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.

Harris, P., & MacFarlane, A. (1974). The growth of the effective visual field from birth to seven weeks. Journal of Experimental Child Psychology, 18, 340-348.

Hassett, J., & Danforth, D. (1982). Introduction to the cardivascular system. In J.T. Cacioppo & R. E. Petty (Eds.), Perspectives in cardiovascular psychophysiology (pp. 4-18), New York: The Guilford Press.

Heilman, K.M., Watson, R.T., Valenstein, E., & Goldberg, M.E. (1987). Attention: Behavior and neural mechanisms. In V.B. Mountcastle, F. Plum, & S.R. Geiger (Eds.), Handbook of physiology, Section 1: The nervous system (Vol V, pp. 461-481). Bethesda, MD: American Physiological Society.

Hicks, J.M., & Richards, J.E. (1998). The effects of stimulus movement and attention on peripheral stimulus localization by 8- to 26-week-old infants. Infant Behavior and Development, 21, 571-589.

Hood, B.M., & Atkinson, J. (1993). Disengaging visual attention in the infant and adult. Infant Behavior and Development, 16, 405-422.

Hunter, M.A., Ross, H.S., & Ames, E.W. (1982). Preferences for familiar or novel toys: Effect of familiarization time in 1-year-olds. Developmental Psychology, 18, 519-529.

Hunter, S.K., & Richards, J.E. (2003). Peripheral stimulus localization by 5- to 14-week-old infants during phases of attention. Infancy, 4, 1-25.

Izard, C. E., Porges, S. W., Simons, R. F., Haynes, O. M., Parisi, M., & Cohen, B. (1991). Infant cardiac activity: Developmental changes and relations with attachment. Developmental Psychology, 27, 432-439.

Jankowksi, J.J., & Rose, S.A. (1997). The distribution of attention in infants. Journal of Experimental Child Psychology, 65, 127-140.

Jennings, J.R. (1986). Bodily changes during attention. In M.G.H. Coles, E. Donchin & S.W. Porges (Eds.), Psychophysiology: Systems, processes, and applications (pp. 268-289), New York: Guilford Press.

Kagan, J., Kearsley, R., & Zelazo, Pl (1978). Infancy. Cambridge, MA: Harvard University Press.

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

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.

Keen, R.E., Chase, H.H., & Graham, F.K. (1965). Twenty-four hour retention by neonates of an habituated heart rate response. Psychonomic Science, 2, 265-266.

Lacey, J.I. (1959). Psychophysiological approaches to the evaluation of psychotherapeutic process and outcome. In E.A. Rubinstein & M.B. Parloff (Eds.). Research in psychotherapy (pp. 160-208). Washington, DC: American Psychological Association.

Lacey, J. I., Kagan, J., Lacey, B. C., & Moss, M. A. (1962). The visceral level: Situational determinants and behavioral correlates of autonomic response patterns. In P. Knapp (Ed.), Expression of the emotions in man (Pp. 161-196). New York: International Universities Press.

Lacey, J.I., & Lacey, B.C. (1958). The relationship of resting autonomic activity to motor impulsivity. In, The brain and human behavior (Proceedings of the Association for Research in Nervous and Mental Disease, pp 1257-1290). Baltimore, MD: Williams & Wilkins.

Lang, A. (1990). Involuntary attention and physiological arousal evoked by structural features and emotional content in TV commercials. Communication Research, 17, 275-299.

Lansink, J.M., & Richards, J.E. (1997). Heart rate and behavioral measures of attention in 6-, 9-,and 12-month-old infants during object exploration. Child Development. 68, 610-620.

Lewis, M., Kagan, K., Campbell, H., & Kalafat, J. (1965). The cardiac response as a correlate of attention in infants. American Psychologist, 20, 478 (Abstract)

Lipton, E.L., & Steinschneider, A. (1964). Studies on the psychophysiology of infancy. Merrill- Palmer Quarterly, 10, 103-177.

Maikranz, J.M., Colomb, J., Richman, W.A., & Frick, J.E. (2000). Autonomic correlates of individual differences in sensitization and look duration during infancy. Infant Behavior and Development, 23, 137-151.

MacFarlane, A., Harris, P., & Barnes, I. (1976). Central and peripheral vision in early infancy. Journal of Experimental Child Psychology, 21, 532-538.

McCall, R.B., & Kagan, J. (1967). Stimulus-schema discrepancy and attention in the infant. Journal of Experimental Child Psychology, 5, 381-390.

Mesulam, M.M. (1983). The functional anatomy and hemispheric specialization for directed attention. Trends in Neuroscience, 6,384-387.

Moruzzi, G.,& Magoun, H.W.(1949). Brain stem reticular formation and activation of the EEG. Electroencephalography and Clinical Neurophysiology, 1,455-473.

Nelson, C.A., & Collins, P.F. (1991). Event-related potential and looking-time analysis of infants' responses to familiar and novel events: Implications for visual recognition memory. Developmental Psychology, 27, 50-58.

Nelson, C.A., & Collins, P.F. (1992). Neural and behavioral correlates of visual recognition memory in 4- and 8-month-old infants. Brain and Cognition, 19, 105-121.

Oakes, L. A., Madole, K. L., & Cohen, L. B. (1991). Infant object examining: Habituation and categorization. Cognitive Development, 6, 377-392.

Oakes, L. M., & Tellinghuisen, D. J. (1994). Examining in infancy: Does it reflect active processing? Developmental Psychology, 30, 748-756.

Picton, T.W., Bentin, S., Berg, P., Donchin, E., Hillyard, S.A., Johnson, R. Jr., Miller, G.A., Ritter, W., Ruchkin, D.S., Rugg, M.D., & Taylor, M.J. (2000). Guidelines for using human event-related potentials to study cognition: Recording standards and publication criteria. Psychophysiology, 37, 127-152.

Pomerleau, A., & Malcuit, G. (1981). State effects on concomitant cardiac and behavioral responses to a rocking stimulus in human newborns. Infant Behavior and Development, 4, 163-174.

Pomerleau-Malcuit, A., & Clifton, R.K. (1973). Neonatal heart-rate response to tactile, auditory and vestibular stimulation in different states. Child Development, 44, 485-496.

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 (Vol 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 (Vol 2, pp. 111-134), Greenwich, CT: JAI Press.

Porges, S.W. (1985). Spontaneous oscillations in heart rate: Potential index of stress. In P.G. Mogberg (Ed.) Animal stress: New directions in defining and evaluating the effects of stress. Bethesda, MD: American Physiological Society

Porges, S. W. (1992). Autonomic regulation and attention. In B. A. Campbell, H. Hayne, R. Richardson (Eds.), Attention and information processing in infants and adults: Perspectives from human and animal research. (pp. 201-223). Hillsdale: Lawrence Erlbaum Associates.

Porges, S.W. (2001). The polyvagal theory: Phylogenetic substrates of a social nervous system. International Journal of Psychophysiology, 42, 123-146.

Porges, S.W., & Bohrer, R.E. (1990). Analyses of periodic processes in psychophysiological research. In J.T. Cacioppo & I.G. Tassinary (Eds.), Principles of psychophysiology: Physical, social, and inferential elements (pp. 708-753). New York: Cambridge University Press.

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

Porter, F.L. (2001). Vagal tone. In L. Singer & P. Zeskind (Eds.), Biobehavioral assessment of the infant (pp.100-124), New York: The Guilford Press.

Porter, C.L., Bryan, Y., & Hsu, H. (1995). Physiological markers in early infancy: Stability of 1-to 6-month vagal tone. Infant Behavior and Development, 18, 363-367.

Posner, M.I. (1995). Attention in cognitive neuroscience: An overview. In Gazzaniga, M.S. (Eds.), Cognitive neurosciences (pps. 615-624). Cambridge, MA: MIT.

Posner, M.I., & Petersen, S.E. (1990). The attention system of the human brain. In W.M. Cowan (Ed.), Annual Review of Neuroscience, 13, 25-42.

Reed, S.F., Ohel, G., David, R., & Porges, S.W. (1999). A neural explanation of fetal heart rate patterns: A test of the polyvagal theory. Developmental Psychobiology, 35, 108-118.

Reynolds, G.D., & Richards, J.E. (2003). Infant attention and cortical sources of ERP for recognition of briefly presented visual stimuli. Unpublished poster presented at the biennial meeting of the Society for Research in Child Development, Tampa, FL.

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

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

Richards, J.E. (1986). Power spectral analysis quantification of respiratory sinus arrhythmia. Psychophysiology, 23, 414 (Abstract).

Richards, J.E. (1987). Infant visual sustained attention and respiratory sinus arrhythmia. Child Development, 58, 488-496.

Richards, J.E. (1988a). Heart rate changes and heart rate rhythms, and infant visual sustained attention. In P.K. Ackles, J.R. Jennings & M.G.H. Coles (Eds.), Advances in psychophysiology (Vol 3, pp 189-221), Greenwich, CT: JAI Press.

Richards, J.E. (1988b). Heart rate offset responses to visual stimuli in infants from 14 to 26 weeks of age. Psychophysiology, 25, 278-291.

Richards, J.E. (1989). Development and stability of HR-defined, visual sustained attention in 14, 20, and 26 week old infants. Psychophysiology, 26, 422-430.

Richards, J. E. (1994). Baseline respiratory sinus arrhythmia and heart rate responses during sustained visual attention in preterm infants from 3 to 6 months of age.Psychophysiology, 31, 235-243.

Richards, J.E. (1995a). Infant cognitive psychophysiology: Normal development and implications for abnormal developmental outcomes. In T.H. Ollendick & R.J. Prinz (Eds.), Advances in Clinical Child Psychology (Vol 17, pps 77-107). New York: Plenum Press.

Richards, J.E. (1995b). Reliability of respiratory sinus arrhythmia in R-R intervals, in 14-, 20-, and 26-week-old infants. Infant Behavior and Development, 18, 155-161.

Richards, J.E. (1997a). Effects of attention on infants' preference for briefly exposed visual stimuli in the paired-comparison recognition-memory paradigm. Developmental Psychology, 33, 22-31.

Richards, J.E. (1997b). Peripheral stimulus localization by infants: Attention, age and individual differences in heart rate variability. Journal of Experimental Psychology: Human Perception and Performance, 23, 667-680.

Richards, J.E. (1998). Focusing on visual attention. Early Development and Parenting, **7**, 153-158.

Richards, J.E. (2001). Attention in young infants: A developmental psychophysiological perspective. In C.A. Nelson and M. Luciana (Eds.), Handbook of developmental cognitive neuroscience (pp. 321-338). Cambridge, MA, US: MIT Press.

Richards, J.E. (2003). Attention affects the recognition of briefly presented visual stimuli in infants: An ERP study. Developmental Science, 6, 312-328.

Richards, J.E., & Anderson, D.R. (in press). Attentional inertia in children's extended looking at television. Advances in Child Development and Behavior, 32.

Richards, J.E., & Casey, B.J. (1990). Heart rate variability during attention phases in young infants. Psychophysiology, 27.

Richards, J. E., & Casey, B. J. (1991). Heart rate variability during attention phases in young infants. Psychophysiology, 28, 43-53.

Richards, J. E., & Casey, B. J. (1992). Development of sustained visual attention in the human infant. In B. A. Campbell, H. Hayne, R. Richardson (Eds.), Attention and information processing in infants and adults: Perspectives from human and animal research. (pps. 30-60). Hillsdale: Lawrence Erlbaum Associates.

Richards, J.E., & Cronise, K. (2000). Extended visual fixation in the early preschool years: look duration, heart rate changes, and attentional inertia. Child Development, 71, 602-620.

Richards, J.E., & Hunter, S.K. (1997). Peripheral stimulus localization by infants with eye and head movements during visual attention. Vision Research, 37, 3021-3035

Richards, J.E., & Hunter, S.K. (1998). Attention and eye movement in young infants: Neural control and development. In J.E. Richards (Ed.), Cognitive neuroscience of attention: A developmental perspective. Hillsdale, NJ: Lawrence Erlbaum Press.

Richards, J.E., & Hunter, S.K. (2002). Testing neural models of the development of infant visual attention. Developmental Psychobiology, 40, 226-236.

Richards, J.E., & Lansink, J.M. (1998). Distractibility during visual fixation in young infants: The selectivity of attention. In C. Rovee-Collier (Ed.), Advances in Infancy Research, (Volume 13, pp. 407-444). Norwood, NJ: Ablex Publishing Co.

Richards, J.E., & Turner, E.D. (2001). Distractibility during extended viewing of television in the early preschool years. Child Development, 72, 963-972.

Robbins, T. W., & Everitt, B. J. (1995). Arousal systems and attention. In Gazzaniga, M.S. (Eds.), Cognitive neurosciences (pp. 703-720). Cambridge, MA: MIT.

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

Rose, S.A., Gottfried, A.W., Melloy-Carminar, P., & Bridger, W.H. (1982). Familiarity and novelty preferences in infant recognition memory: Implications for information processing. Developmental Psychology, 18, 704-713.

Ruff, H.A. (1986). Components of attention during infants' manipulative exploration. Child Development, 57, 105-114.

Ruff, H. A., Capozzoli, M., & Saltarelli, L. M. (1996). Focused visual attention and distractibility in 10-month old infants. Infant Behavior and Development, 19, 281-293.

Schectman, V.L., Kluge, K.A., & Harper, R.M. (1988). Time-domain system for assessing variation in heart rate. Medical and Biological Engineering and Computing, 26, 367-373.

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

Smith, J.J, & Kampine, J.P. (1984). Circulatory physiology: The essentials. Baltimore, MD: Williams & Wilkins.

Starzl,T.E.,Taylor,C.W.,& Magoun,H.W.(1951). Ascending conduction in reticular activating system, with special reference to the dienchephalon. Journal of Neurophysiology, 14, 461-477.

Stifter, C.A., & Fox, N.A. (1990). Infant reactivity: Physiological correlates of newborn and five-month termperament. Developmental Psychology, 26, 582-588.

Tellinghuisen, D. J. & Oakes, L. M. (1997). Distractibility in infancy: The effects of distractor characteristics and type of attention. Journal of Experimental Child Psychology, 64, 232- 254.

Tronick, E. (1972). Stimulus control and growth of the infants' effective visual field. Perception and Psychophysics, 11, 373-376.

Wagner, S.H., & Sakovitz, L.J. (1986). A process analysis is infant visual and cross-modal recognition memory: Implications for an amodal code. Advances in Infancy Research, 4, 195-217.

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.

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

Zeaman, D., Deane, G., & Wegner, N. (1954). Amplitude and latency characteristics of the conditioned heart response. Journal of Psychology, 37, 235-250.