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Infant Cognitive Psychophysiology

Normal Development and Implications for Abnormal Developmental Outcomes

JOHN E. RICHARDS

1. Introduction

Psychophysiology may be defined as "the study of relations between psychological manipulations and resulting physiological responses, measured in the living organism, to promote understanding of the relation between mental and bodily processes" (Andreassi, 1989). The main impetus of psychophysiology is to relate psychological behavior to underlying physiological systems. Psychophysiology is also the study of parallel relations between psychological behavior and physiological systems. Psychophysiological research typically uses noninvasive recording methods and human subjects. Other scientific areas, such as physiological psychology, psychobiology, and behavioral neuroscience study physiological–psychological relations. These fields use more invasive physiological measures and, as a result, use animal models rather than human subjects in the study of behavior.

Cognitive psychology is the study of behavior such as attention, memory, information processing, thinking, and language. Cognitive psychophysiology uses physiological functions to study these functions. Cognitive psychophysiology sometimes merely uses physiological systems in

JOHN E. RICHARDS • Department of Psychology, University of South Carolina, Columbia, South Carolina 29208.

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the study of cognitive psychology. Many cognitive psychophysiologists are interested in how physiological systems (e.g., brain, central nervous system, autonomic nervous system) affect cognitive behavior.

Researchers interested in infant cognitive development have turned to psychophysiological theories and methods to aid their study. This chapter reviews some studies of infant cognitive development that have used psychophysiological models. The focus will be on those research models in which the infant's cognitive development is thought to be inextricably related to the development of the physiological system.

It is not possible to review the entire field of infant cognitive psychophysiology in this chapter. The reader may consult other sources for reviews of infant developmental psychophysiology (e.g., W. Berg & K. Berg, 1987; Porges & Fox, 1986), as well as reviews of the development in infancy of specific systems (e.g., *EEG/ERP*: Courchesne, 1990; Kurtzberg et al., 1984; Nelson, 1993; Salapatek & Nelson, 1985; Vaughan & Kurtzberg, 1992; *Heart Rate*: Finlay & Ivinkis, 1987; Fox & Fitzgerald, 1990; Von Bargen, 1983). Two foci guide the presentation. First, the emphasis is on those research paradigms and models in which complex infant cognitive behaviors are studied. The use of simple stimuli with underlying simple cognitive behavior will not be emphasized. Second, the chapter emphasizes research conducted within the past 10 years, even though infant cognitive psychophysiology has a long history (30 to 40 years). This chapter emphasizes research reflecting recent attempts to integrate theories of infant cognitive development with theoretical models of psychophysiological development. Finally, a brief presentation is given of some research looking at abnormal and high-risk infant development from a cognitive psychophysiological perspective.

2. *Evoked Scalp Potentials*

The study of electrical potentials measured with surface electrodes on the scalp in infants has a long history. There have been two main trends of research. One trend has studied spontaneous electrical activity measured on the scalp, the *electroencephalogram* (EEG). Perhaps the most frequent use of spontaneous EEG has been the patterns of potentials that occur in different sleep states. EEG in sleep states has been studied extensively in newborn and infants. The characteristics of EEG in sleep and waking states are an essential component of the definition of sleep states in infants.

A second trend of research is the study of scalp electrical activity that occurs in response to stimulus challenge, called *evoked scalp potentials*. The evoked scalp potentials have an important advantage over EEG in the study of infant cognitive behavior. Stimuli and experimental manipulations known to have significant psychological consequences may be studied with the evoked EEG at the same time the psychological process is occurring. The evoked scalp potentials and their relation to infant cognitive activity are reviewed in this section.

2.1. *Definition and Methodology*

Scalp potentials are measured with small electrodes placed on the scalp at specified locations. The electrode placement is typically done according to an accepted system, for example, the 10–20 System, in which electrode placement occurs over the frontal, central, temporal, parietal, and occipital portions of the scalp (Jasper, 1958). The electrical potential measured at each location is measured in reference to a common electrode placed on the body near the scalp that does not have electrical activity occurring as a result of brain activity (e.g., ear or ear mastoid). The electrical activity measured on the scalp is generated by the electrical activity of groups of neurons in the brain, summed over large numbers of neurons and synapses. The amplitude of the electrical potential measured at the scalp in infants ranges from 0.1 microvolts to 20–30 microvolts.

Spontaneous EEG consists of constantly varying electrical potentials that occur under a variety of stimulus conditions. However, psychophysiologists are interested in brain activity occurring as a result of psychological processes. Thus, EEG activity synchronous with externally observable events, and thought to be occurring simultaneously with psychological activity, is of most interest. These scalp potential changes are labeled *event-related potential* (ERP).

The ERP is extracted from spontaneous EEG activity with averaging procedures. The spontaneous EEG activity is semirandom with respect to the events manipulated by the experimenter. The ERP activity is time-locked to those events. Spontaneous EEG activity is generated at several sources in the brain, whereas the ERP activity synchronous with the psychological activity is generated by only a few sources. Thus, spontaneous EEG activity is much larger than ERP activity. Therefore, averaging from a few (20) to many (100–200) EEG changes following an event will lead to a gradual diminution of the semirandom EEG and an enhancement of the electrical activity specifically linked to the event, and to the concomitant psychological process.

Figure 1 shows two types of ERP. Figure 1a is an example of the *brainstem auditory evoked response*, BAER (or brainstem auditory evoked

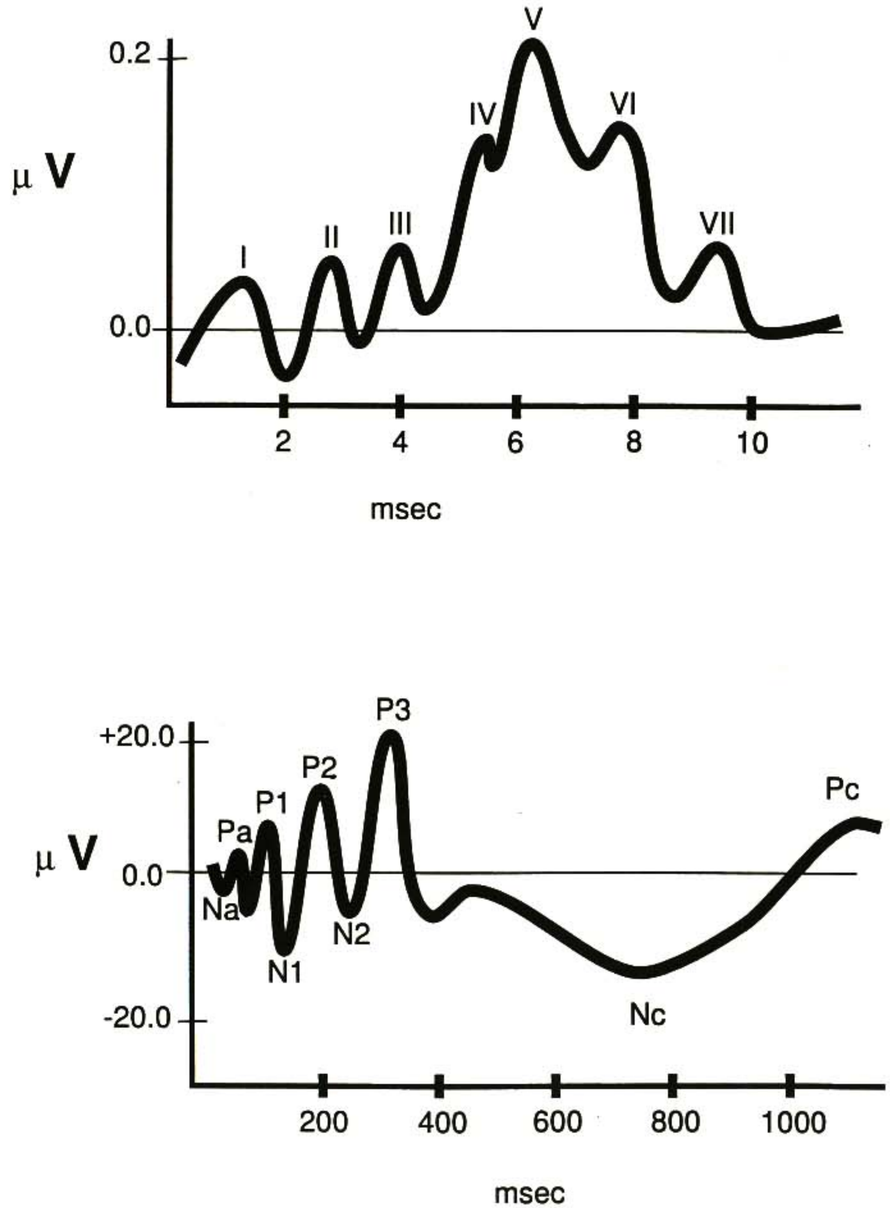


FIGURE 1. A schematic illustration of the evoked response potentials. The top figure shows a brainstem auditory evoked response (BAER) with the seven positive peaks labeled with Roman numerals I to VII. The bottom figure shows an evoked response potential (ERP) with the negative (*N*) and positive (*P*) waves, each occurring approximately at specific msec intervals (e.g., N2 is negative wave occurring approximately 200 msec following stimulus onset). The BAER and ERP components Na, Pa, P1, N1 and P2 are exogenous, and the ERP components N2, P3, Nc, and Pc are endogenous.

potential, BAEP). The BAER has a very short latency, occurring during the first 10 msec following auditory stimuli, and has the smallest amplitude of the evoked potentials. The BAER occurs as a result of electrical activity occurring in the auditory primary sensory pathway. The BAER waves I through IV are known to occur in specific neural groups in this pathway. Figure 1b is an example of later-occurring electrical activity in the ERP. The later ERP activity has components that occur in response to visual, auditory, and somesthetic stimuli. The earliest components (e.g., Pa, Na, P1, N1, and P2), along with the BAER, are labeled *exogenous* potentials. They represent neural activity in the sensory pathways that is closely related to the physical properties of the stimulus.

Most of the ERP research with infants has been with exogenous ERP components. These studies have used simple stimuli and experimental conditions to elicit the evoked potentials. This methodology is useful for the study of sensory processing and for understanding how the developing infant processes the psychophysical properties of sensory stimuli. This approach may also be extremely useful in the understanding of how cortical maturation is reflected in the ERP components in the early phases of information processing (Courchesne, 1990; Vaughan & Kurtzberg, 1992). Reviews of such work can be found in Courchesne (1990), Kurtzberg et al. (1984), Nelson (1993), Salapatek and Nelson (1985), Vaughan & Kurtzberg (1989, 1992), among others.

The later-occurring potentials in Figure 1b (N2, P3, Nc, Pc, and N400) are labeled *endogenous* potentials. These potentials are affected by psychological processes, such as discrimination difficulty, attention, expectancy, and intention. They are unrelated to physical changes in the stimulus, and may occur in the absence of external stimulation. The endogenous potentials are of more interest to cognitive psychophysiology because they are related to complex psychological processes that occur during cognitive activity.

2.2. *Infant Recognition Memory*

The study of endogenous potentials in infant cognitive psychophysiology has had two influences. First, the P3 (P300; P3a; P3b) is an ERP component that is known to be related in adults to several psychological processes. It is generally evoked in the "oddball" paradigm, which consists of one stimulus set being presented frequently (e.g., 80%) and another infrequently (20%). The P3 is an ERP component of positive electrical potential, which occurs at around 300 msec after the stimulus presentation, primarily over the parietal scalp region, and occurs with greater magnitude to the infrequently presented stimulus. Second, investigations by

Courchesne (1977, 1978) with young children older than 2 years has identified two ERP components occurring primarily in children. The Nc is a negative ERP component, has a latency between 400 to 1000 msec is distributed over the frontal and central scalp regions, and is thought to be a sign of enhanced attention to surprising, interesting, or psychologically significant visual or auditory stimuli. The Pc is a positive ERP component, has a latency longer than 1000 msec, has a similar scalp distribution as Nc, and occurs in response to interesting visual or auditory stimuli.

The first publications studying endogenous ERP components in young infants in experimental settings came in 1981. One of those was a study of ERP during the oddball paradigm by Courchesne, Ganz, and Norcia (1981). Courchesne et al. reported data from 10 infants who ranged in age from 4 to 7 months. The infants were presented with slides of two women for 100 msec. One slide was presented on 88% of the trials, and the other on 12%. The frequently presented face should become familiar to the infant over the course of stimulus presentation, whereas the one presented infrequently should be a discrepant or novel stimulus (e.g., the "oddball" stimulus). Research with older children and adults showed that the endogenous component P3 occurs over the parietal region, whereas the Nc and Pc components occur over the frontal region (Courchesne, 1977, 1978). In the Courchesne et al. (1981) study, EEG was recorded over the frontal and parietal regions. By recording at these sites, they could determine if these endogenous potentials existed in young infants, and distinguish them by scalp location and relation to the frequent/infrequent events.

The Courchesne et al. (1981) study had two main findings. First, a significant negativity occurred in the ERP in all 10 infants over the frontal region, with a latency of about 500–700 msec. Because of its latency and scalp distribution, it was concluded this was a Nc component (cf. Courchesne, 1977, 1978). This negative ERP occurred for both the familiar and the novel face, but was largest for the infrequently presented face. Figure 2 (bottom tracing) shows the tracing from the ERP to the frequent and infrequent faces. The difference between the two types of stimuli is highlighted by the crosshatching on the recordings occurring at the Fz (frontal) site. Second, a late positive component in the ERP occurred, primarily over the frontal electrode sites (Fig. 2). This component had a latency and distribution like that found with older children for a Pc component. This infant Pc component was not different in amplitude for the familiar and the novel faces. No evidence was found for a positive ERP component near 300 msec over the parietal region (i.e., the P3 component found in research with older children and adults).

The finding of late ERP components in 4- to 7-month-olds that were

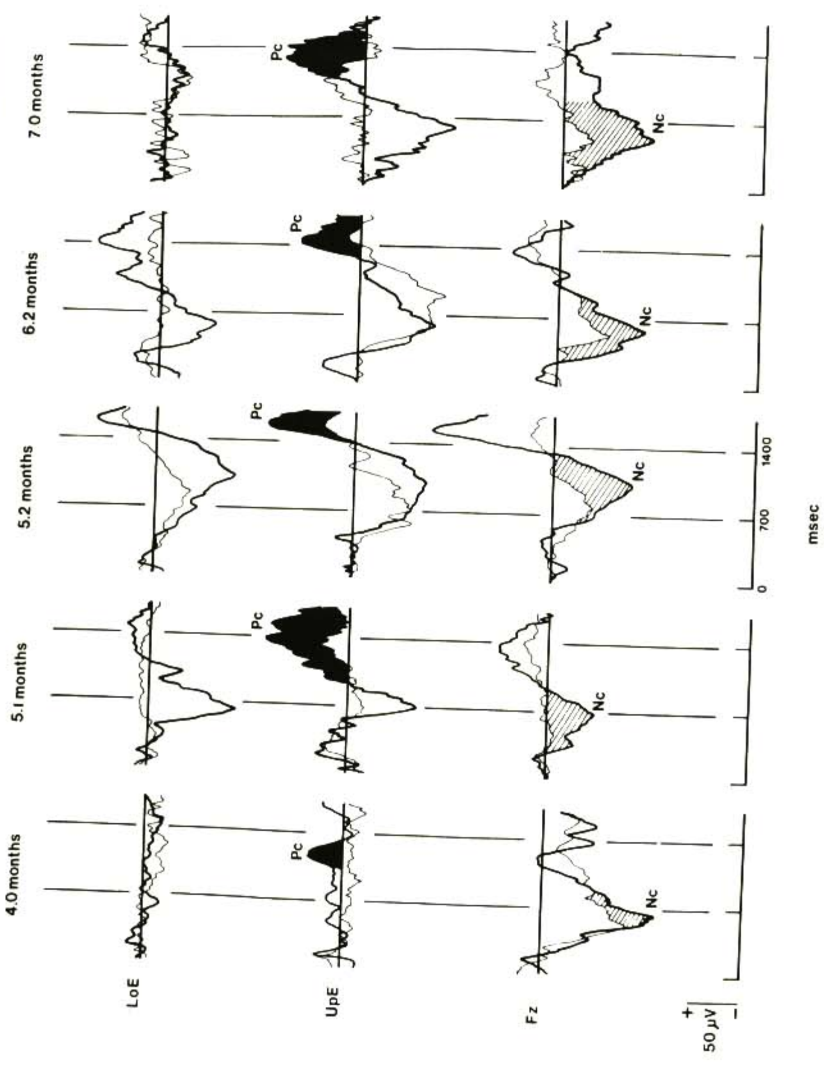


FIGURE 2. Event-related potentials from electrodes near the eye (LoE and UpE) and scalp electrodes on the frontal scalp location (Fz) to frequent (thin lines) and infrequent (thick lines) faces from five infants ranging in age from 4 to 7 months. The crosshatching represents the difference between the two stimuli types. Reprinted by permission from Courchesne et al., 1981. Copyright 1981 Society for Research in Child Development.

related to the frequent/infrequent manipulation was extended to younger and older infants by Karrer and Ackles (1987). Karrer and Ackles used infants at ages 6 weeks, 6 months, 12 months, and 18 months. They used a frequent/infrequent presentation of stimuli similar to Courchesne et al. (1981), with checks and random stimuli for the youngest group, faces for the 6-month-olds, and pictures of stuffed animals and toys for the older infants. They recorded the ERP from frontal, central, parietal, and occipital sites. Their results were similar to those of Courchesne et al. (1981). There was a large negative ERP component around 600 msec following stimulus presentation. For the three oldest groups, at the central scalp region, the amplitude of this component was larger for the infrequent than for the frequent stimulus. There was a significant Nc response at the frontal recording location that was not differentially affected by the oddball presentation. No large negativity was found at the parietal or occipital sites. The Nc component at both the frontal and central scalp locations increased in magnitude over the age range of 6 to 18 months. Studies by Kurtzberg and associates (e.g., Kurtzberg, Vaughan, & Novak, 1986) with speech sounds ("da" and "ta") presented frequently/infrequently extended the finding of a Nc component to auditory stimuli.

These studies have two findings. First, significant ERP changes are found in conjunction with the frequent/infrequent presentation of stimuli. This indicates recognition by the infant of the relative novelty/familiarity, or probability of the stimuli. As such, it shows a recognition memory for the stimulus, and an increased attention level to the novel stimulus. This parallels what has been found in adults with the P3 ERP component. It complements the finding that infants at this age in visual preference paradigms spend more time looking at a novel stimulus than at a familiar one. The possibility that there are developmental changes in these components (Karrer & Ackles, 1987, 1988) indicates the possibility of assessing developmental changes in recognition memory.

The second finding in these studies is the absence of a ERP component that could be related to the P3 found in adults. The components that were found in these studies with infants were at different scalp sites (frontal, central, rather than parietal) and at different latencies (700 msec, 1300 msec, rather than 300 msec than the P3 component. The frequent/infrequent presentation style was an analog to the oddball paradigm used with adults, and had similar effects in all of the cited studies on the Nc component, but no P3 component was found. It has been argued that the exogenous ERP's in infants, reflecting sensory processing, occur at 200 to 300 msec so that a P3 sensitive to psychological variables might be physically impossible (Vaughan & Kurtzberg, 1992). It has been concluded by Courchesne (1990; Courchesne & Yeung-Courchesne, 1988) that the P3 does not exist in infants, and emerges as a distinct ERP component late in the second year of life.

A different set of research findings has reported a probability effect with positive waves in the ERP around 300–600 msec. The first of these, published in the same year as the Courchesne et al. (1981) study, was done by Hoffman, Salapatek, and Kuskowski (1981). They presented 3-month-old infants with high-contrast square wave gratings for 500 msec for several trials. Their procedure differed from the studies cited earlier in that they had a *familiarization phase* that consisted of a single stimulus presented for 40 trials. Then, in a *test phase*, the familiar stimulus was presented for 80% of the time (frequent-familiar) and a new stimulus was presented for 20% of the time (infrequent-novel). They recorded scalp potentials at occipital and parietal (Study 1), and frontal (Study 2) locations, during the stimulus. A positive ERP component in the occipital scalp leads was found around 300–400 msec following stimulus presentation. This ERP component was larger to the infrequent-novel stimulus ERP in the test phase compared to the ERP during the familiarization phase. They did not find a difference between the frequent-familiar and infrequent-novel stimuli presented in the test phase. Nelson and Salapatek (1986), using a similar test protocol but employing longer recording intervals, found a negative ERP component at the central leads between 500 to 700 msec distinguishing the familiar phase ERP from the test phase infrequent-novel stimulus. A positive component was found at central and frontal leads at longer intervals (900 msec) that distinguished between the frequent-familiar and infrequent-novel stimuli on the test trials.

The studies of Courchesne et al. (1981) and Karrer and Ackles (1987) reported the later components (Nc and Pc), whereas the Hoffman et al. (1981) and the Nelson and Salapatek (1986) studies reported earlier positive ERP components. There were several differences between these studies that might account for the different results. A major difference is the use of a familiarization phase in the latter studies, and the lack of such a phase in the former ones. The use of a familiarization phase is probably important in this research. In the studies without the familiarization phase, it is likely that a memory for the frequently presented stimulus is gradually building up over the course of the presentations, whereas the infrequently presented stimulus retains its relative novelty. A possible confound with each of these studies is that the "infrequent" stimulus is also the "novel" stimulus. Thus, it may not be the "novelty" of the stimulus that elicits the ERP differences, but the mere "frequency."

A study by Nelson and Collins (1991) addressed these problems. They recorded EEG over several scalp locations in 6-month-old infants, with long enough recording intervals to detect the Nc and Pc components. A familiarization phase consisted of presenting two facial stimuli with equal probability to the infants on multiple trials. The test phase had three types of presentations: (1) a familiar stimulus presented frequently (60%; frequent-familiar); (2) a stimulus from the familiarization period but presented infrequently in the test phase (20%; infrequent-familiar); and (3) a stimulus never presented, and presented infrequently (20%; infrequent-novel). This study was unique in that the infrequent-novel stimulus was a different face on each trial, thus prohibiting any familiarization to the novelty of the face. This study could compare the relative probability of the stimulus separate from its novelty (frequent-familiar compared with infrequent-familiar), and the novelty of the stimulus separate from its relative probability (infrequent-familiar compared with infrequent-novel).

The most important results from this study were ERP differences found in the central scalp locations (Fig. 3). First, there were no differences before 750 msec or after 1400 msec in the three conditions. Second, at the central lead between 750 and 1400 msec, there was an increased positivity in the test-phase ERP to the infrequent-familiar stimulus relative to the frequent-familiar (or to the familiar stimuli during the familiarization phase). Thus, though the infrequent-familiar should be recognizable to the infant, its relative probability alone (a frequency effect) was sufficient for infants to distinguish it from the frequently presented familiar stimulus. There was also a "novelty" effect. The ERP to the frequent-familiar stimulus was positive at this latency, whereas the ERP to the infrequent-novel stimulus was negative. The ERP to the infrequent-novel stimulus was similar to the Nc component found in the previous studies. Thus, in the oddball paradigms, modified from adult versions, infants are responsive both to stimulus novelty and to the frequency of stimulus occurrence. Nelson and his colleagues have used this technique in several recent studies to examine recognition memory and frequency effects in infants (e.g., Nelson & Collins, 1992; Nelson & deRegnier, 1992; Nelson, Ellis, Collins, & Lang, 1990; Nelson, Henschel, & Collins, 1993; see review by Nelson, 1993). An important developmental finding from some of those studies is that at 4 months of age there is no difference between the ERP's to the three conditions, whereas by 6 months (Nelson & Collins, 1991) or 8 or 12 months (Nelson & Collins, 1992; Nelson & deRegnier, 1992) the ERP components differ.

The studies cited thus far indicated that very late components (e.g., greater than 700 msec) of the ERP distinguish the oddball stimulus from the familiar stimulus, whereas earlier components (e.g., around 300 msec) do not. One relatively recent study with 5- to 10-month-old infants reported an ERP component that was very similar in duration and topography to the adult P3 (McIssac & Polich, 1992). That study used the pres-

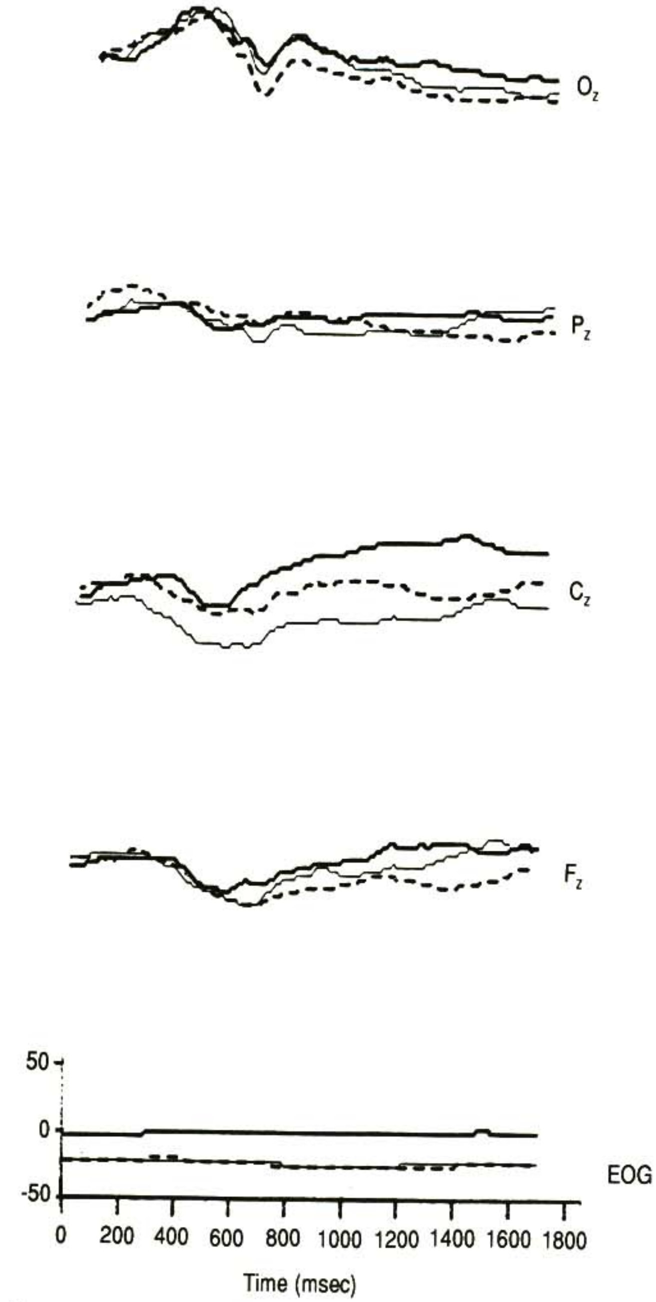


FIGURE 3. Event-related potentials for the test phase in a recognition memory study. These come from the occipital, parietal, central, and frontal scalp recording locations (Oz, Pz, Cz, Fz). The data are from the frequent-familiar (dashed line), infrequent-familiar (thick solid line) and infrequent-novel (thin solid line). Significant differences between conditions occurred at Cz. Reprinted by permission from Nelson & Collins, 1991. Copyright 1981 American Psychological Association.

entation of tones (1000 or 2000 Hz), with a fixed presentation of 10 auditory stimuli, with the oddball or "target" stimulus occurring in the 7th, 8th, 9th, or 10th position in each 10-tone sequence. They found an enhanced positive component of the ERP around 600 msec in the infants to the target (infrequent-novel) tone. Adults tested in the same study showed positive ERP component that was much larger, had a larger frequent/infrequent difference, and had latencies around 300 msec. The largest ERP differences for both infants and adults were in the central and parietal recording locations. This finding of a P3-like component in the infant ERP is different from that found with infant subjects for visual stimuli or for previous studies with auditory stimuli (e.g., Kurtzberg et al., 1986). This finding needs to be replicated with testing protocols similar to those used in past research (e.g., Courchesne et al., 1981; Nelson & Collins, 1991) in order to compare it with the previous studies. It is promising in the selection of a test protocol that elicits a significant ERP component with scalp topography similar to that found with adults.

2.3. *Implications for Abnormal Development*

There is a long history of using EEG and ERP in the study of abnormal infant development. Almost all of the work in this area with infants has been with spontaneous EEG or with the exogenous ERP components. The work with exogenous ERP components of abnormal infants has focused on Down's syndrome infants, infants and children with autism, preterm infants, infants with respiratory difficulties at birth, infants with developmental delays, and infants with hearing and visual problems (Courchesne & Yeung-Courchesne, 1988; Kurtzberg, 1982; Salapatek & Nelson, 1985; Vaughan & Kurtzberg, 1989). The endogenous ERP components and ERP components during complex cognitive processes have not been extensively investigated in abnormal infant development. The studies with the endogenous ERP components of interest to infant cognitive psychophysiology for the assessment or diagnosis of abnormal children have evaluated older children (Courchesne & Yeung-Courchesne, 1988).

The study of abnormal development with endogenous ERP's would be useful. It is usually assumed that prenatal and perinatal risk factors, particularly medical risk factors, have their effects on cognitive or intellectual functioning carried through childhood by changing CNS systems responsible for information processing. These structures may prohibit appropriate interaction with the environment in infancy, retarding appropriate developmental changes throughout early childhood, leading to poor cognitive performance in the early school years. Although with exogenous or sensory ERP's some of these affected areas can be identified

in infants, it is not basic sensory processes for which the risk exists—it is higher cognitive functioning. Thus, the psychophysiological tasks that evaluate cognitive activity related to physiological systems would be inherently more useful in identifying abnormal cognitive behavior in infants that should be related to abnormal cognitive outcome in childhood. The ERP/recognition–memory relation might be useful for identifying infants at risk for later poor intellectual function. Some behavioral tests of infant recognition memory are the best predictors in young infants of normal intellectual outcome at 5 years of age (Fagan, 1992; Thompson, Fagan, & Fulkner, 1991). This prediction may be aided by examining indicators of the underlying physiological abnormality, if any, with ERP recording.

There is at least one example of the use of endogenous ERP with infants having developmental abnormalities. Karrer and Ackles (1988) recorded Nc in infants with Down's syndrome at ages 6 months through 2 years and found the physical characteristics (latency, amplitude, duration) of this endogenous ERP component to be similar in the infants with Down's syndrome and normal infants. The normal infants showed larger Nc amplitudes to the oddball stimuli than to repeated stimuli, whereas the infants with Down's syndrome showed the same Nc amplitude to both novel and repeated stimuli (Figure 4). The infant with Down's syndrome was thus responding to the stimulus, but did not discriminate the novel properties or show recognition memory. Older children with Down's syndrome show abnormal endogenous potentials associated with cognitive processing (Courchesne, 1988; Courchesne & Yeung-Courchesne, 1988).

3. *Evoked Heart Rate Changes*

The most common measure used by psychophysiologists studying infants is heart rate. Heart rate (HR) is obtained from surface electrodes on the chest, arms, or legs, derived from the electrocardiogram (ECG). As with EEG, there have been studies of spontaneous HR and evoked HR in infant cognitive-psychophysiological research. Unlike the EEG/ERP research, there have been numerous studies of evoked HR changes during complex cognitive activity in infants. The ECG is much easier to measure in behavioral situations, can be used in single-trial analyses, requires less signal processing, and uses inexpensive and easily used recording equipment.

At one level, HR might appear to be not as closely related as EEG/ERP to "cognitive" activity because of its relative "physiological distance" from the brain. However, HR has been found to be functionally related to many cognitive activities. Recent understanding of the brain systems involved in HR control have led to a sophisticated understanding of the relation of HR

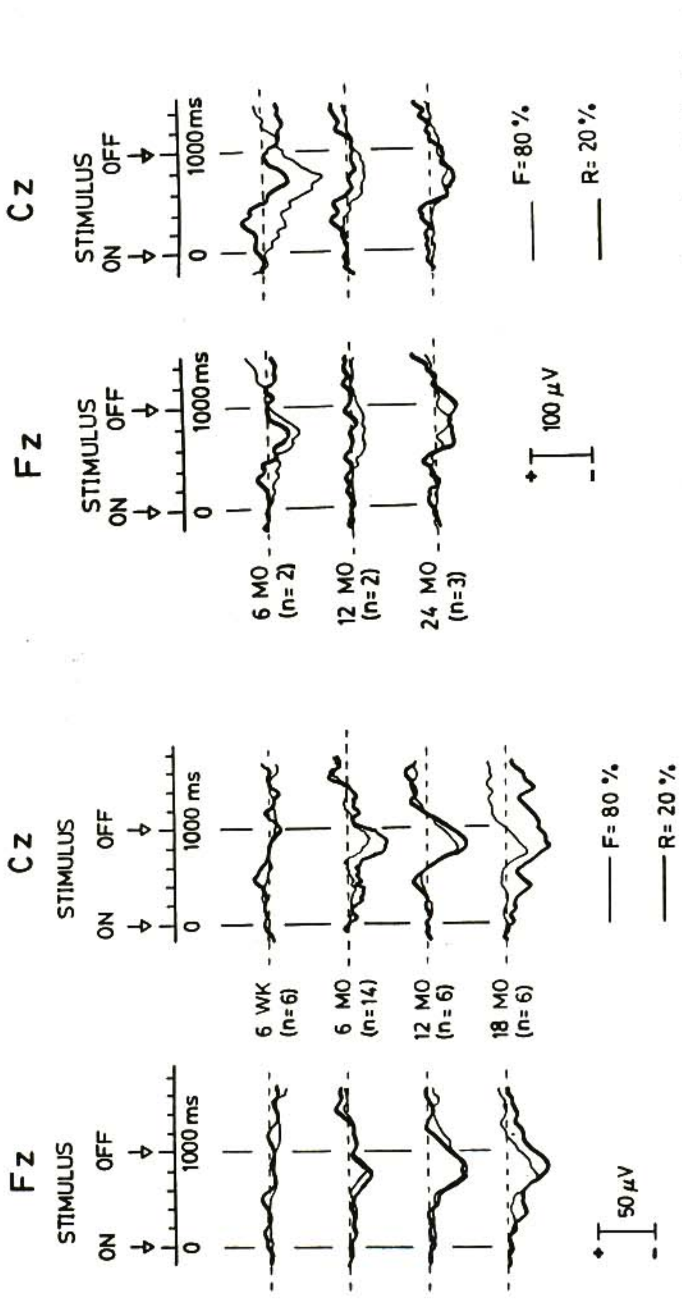


FIGURE 4. Event-related potentials to normal and Down's syndrome infants from 6 weeks through 2 years of age, shown from the frontal and central scalp recording locations (Fz, Cz). The data are from frequently presented stimuli (thin lines) and infrequently presented stimuli (thick lines). The Fz/Cz recordings on the left are from normal infants, and show larger Nc responses to the infrequent stimuli in the Cz lead beginning at 6 months of age. The recordings on the right are from the Down's syndrome infants, and show slightly larger Nc responses to the *frequent* rather than the infrequent stimuli, or show no difference between the frequent and infrequent stimuli. Reprinted by permission from Karrer & Ackles, 1988. Copyright 1988 Prentice-Hall, Inc.

to the brain. Spontaneous and evoked HR are both indices of arousal and attention systems, index brainstem, vagal and frontal lobe functioning, and are closely related to many psychological behaviors. The HR changes occurring in response to cognitive challenges, evoked HR, will be emphasized in this section.

3.1. *Definition and Methodology*

The electrocardiogram (ECG) is a strong electrical signal that may be recorded over the entire body. Electrode placement is not critical in measuring heart rate (HR). For convenience, the ECG is typically recorded by surface electrodes placed on the chest. The ECG is generated by electrical activity in the divisions of the heart as it pumps blood through the lungs and body. The amplitude of the ECG is in several millivolts rather than the microvolt range found with EEG. The ECG consists of several *waves* generated by different parts of the heart, and are labeled *P, Q, R, S,* and *T*. The interval between two R-waves is defined as the *interbeat interval* (IBI, R–R interval). The inverse of the IBI, or the number of beats in a specific time period, defines HR (beats-per-minute, BPM).

The original use of the R-wave for defining a beat was based on convenience rather than physiological rationale. The R-wave is very large relative to the other ECG waves. Psychophysiologists could use a *level-detector* that timed the occurrence of electrical potentials above a certain level, and could set the level such that the R-wave was the only ECG wave reaching that amplitude. The R-wave represents the depolarization of the atrium after the initiation of the heartbeat, and is not really the beginning of the beat. Recently, researchers have begun to use continuous analog-to-digital sampling to identify the peak of the R-wave, or the onset of the P, Q, S, or T waves, to identify different chronometric components of the ECG signal.

Like EEG, spontaneous HR changes occur under a variety of conditions. The HR changes occurring in synchrony with psychological processes or observable psychological activity are of greatest interest. These event-related HR changes are functionally related to several cognitive activities. Unlike EEG, the evoked HR changes are in magnitude several times larger than the spontaneous changes. Thus, the HR changes that are synchronous with psychological activity can be measured without averaging procedures. This has the advantage of allowing single-trial HR changes, manipulations involving several factors in repeated-subjects designs, and the recording of longer experimental sessions than is possible with ERP. Alternatively, HR changes contain less information than do EEG/ERP changes (e.g., Fig. 1).

There have been three or four trends in infant psychophysiological HR research. The first research studies were of the *cardiac orienting response.* There is a sudden deceleration of HR of 8 to 10 bpm in infants 3 months of age and older in response to almost any stimulus. Graham and Clifton (1966) proposed that this HR response was part of the orienting reflex studied by Sokolov (1963). There were a number of studies in the late 1960s and throughout the 1970s that investigated the characteristics of this HR response in infants, the age of its onset and characteristics at different ages, and its relation to infant characteristics (e.g., prematurity, race, sex). This work (like exogenous ERP components in infants) has used simple stimuli and experimental conditions to elicit the HR changes. These studies have been useful for understanding basic infant sensory and perceptual processing, but not very useful for understanding infant cognitive development or infant cognitive behavior. There have been many reviews of this work (e.g., W. Berg & K. Berg, 1987; Finlay & Ivinskis, 1987; Fox & Fitzgerald, 1990).

A second trend in the use of heart rate has been as an index of infant attention. Two characteristics of HR noted by Graham and Clifton, which characterize orienting responses in general, are the magnitude of the response to initial stimulus presentation, and the habituation of the response with repeated stimulus presentation. The first presentation of a novel stimulus evokes large HR changes. With repeated presentations, the HR gradually diminishes so that little or no HR change occurs, (i.e., habituation). When large HR changes are found, it is assumed that the infant is "attending" or "orienting" to a novel stimulus. The lack of HR changes indicates inattention, habituation, or disinterest. These two characteristics of the infant HR response, along with the habituation paradigm, led to the extensive use of HR in studies of infant attention and memory, and other aspects of cognitive development. A third trend in infant HR research has been the study of many other psychological dimensions of infant behavior (emotion, temperament, social interactions, risk status). Reviews of HR in infant attention, cognition, and other behavior, can be found in W. Berg and K. Berg (1987), Fox (1989), Fox and Fitzgerald (1990), and Von Bargen (1983), among others.

3.2. *Infant Sustained Attention*

The study of HR as a manifestation of the *cardiac orienting response,* or as a measure of nonspecific infant attention, is of limited use in understanding infant cognitive behavior. These studies have been unsophisticated in their model of the HR changes and the physiological systems controlling such changes. The HR changes were merely an alternative index of attention, a convenient response if the infant who could not respond with another type of behavioral response (e.g., verbal answers, press a button indicating a choice or reaction time).

The HR changes that occur during stimulus presentation may be broken down into components. Several researchers have hypothesized that the HR changes occurring during stimulus presentation can be broken down into several attention phases (Graham, 1979; Graham, Anthony, & Ziegler, 1983; Porges, 1976; Richards, 1988; Richards & Casey, 1991, 1992). Figure 5 shows the HR changes that occur while 3- to 6-month-old infants view an interesting visual stimulus. This figure illustrates the HR changes that occur during stimulus orienting, sustained attention, and attention termination. Stimulus orienting represents the initial processing of the novelty of the stimulus. Sustained attention amplifies and maintains the stimulus-orienting phase, and detailed stimulus information is processed during this phase. The attention-termination phase is hypothesized to be when the infant fixates on the stimulus following sustained attention, but is not processing information in the stimulus, and is resistant to responding to stimulus change. The phases of sustained attention and attention termination are of more importance to infant cognitive psychophysiology

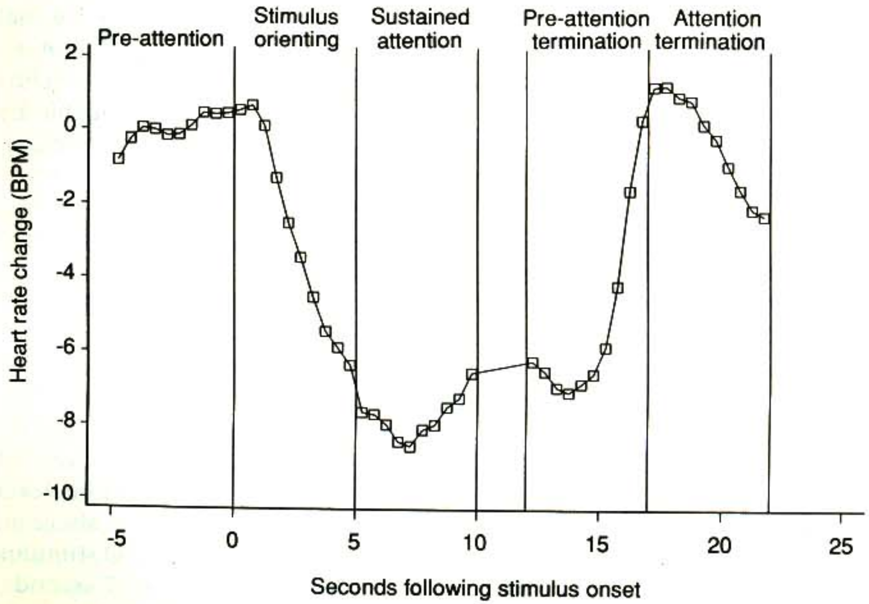


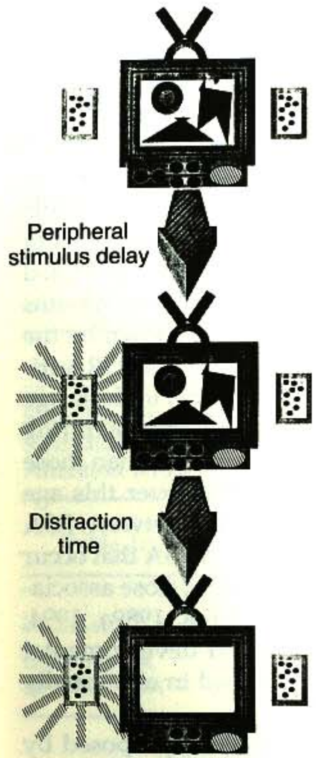
FIGURE 5. Heart-rate changes and hypothesized associated attention phases during fixation of infants to visual stimuli. Reprinted by permission from Richards & Casey, 1991. Copyright 1991 Society for Psychophysiological Research.

than are those of stimulus orienting because the former are thought to be related to complex cognitive activity. In addition, they parse the HR changes so that specific cognitive activity may be indexed during HR changes.

The study of the HR-defined attention phases has been enhanced by the on-line evaluation of HR changes occurring during visual attention. On-line evaluation allows the identification of HR changes as they occur during psychological behavior, and the modification of experimental events based on those changes. The evaluation of HR is done with microcomputer-controlled analog-to-digital conversion of the ECG at high speeds (1 msec, the identification of the R-wave in the ECG, and the software evaluation of HR changes. For example, Richards (1987) defined a significant HR deceleration as a sequence of 5 heartbeats with IBI's greater than the median of the IBI's occurring in a prestimulus interval. This was evaluated immediately after each beat occurred. Once the criterion for HR deceleration was met, then modification of the experimental situation was done to examine the characteristics of the attention phases.

The use of on-line evaluation of HR in the study of sustained attention and attention termination can be found in several studies by Richards and colleagues (e.g., Casey & Richards, 1988; Richards, 1985, 1987, 1989a, 1989b, 1991, 1994; Richards & Casey, 1991; see reviews by Richards, 1988, and Richards & Casey, 1992). These studies presented interesting visual stimuli on a TV monitor to elicit the HR changes. Active processing of the information in the stimulus should occur during sustained attention. During active stimulus processing, the infant should not be distractible by other events. During inattention (e.g., prestimulus or attention termination), the infant should be easily distracted from fixated stimuli by other events.

Distractibility during the HR-defined attention phases has been tested in several studies with infants from 2 to 6 months of age. An interesting stimulus was presented on a centrally located TV monitor. After some delay, a stimulus was presented in the periphery in order to interrupt the fixation on the central stimulus. Figure 6 is a schematic illustration of this procedure. The peripheral stimulus was presented with no central stimulus present (preattention); with the central stimulus fixated, accompanied by a significant HR deceleration (sustained attention); and with the central stimulus fixated, accompanied by a return of HR to its prestimulus level (attention termination). As expected by an understanding of the attention phases, the infants took longer to be distracted by the peripheral stimulus during the lowered, sustained HR deceleration (approximately 7 seconds; Fig. 6), than when HR had returned to its prestimulus level (approximately 3 seconds; Fig. 6) (e.g., Casey & Richards, 1988; Richards, 1987). If the



Peripheral Stimulus Delay	Distraction Time	Localization Percentage
Pre-attention (prestimulus)	1 second	75%
Stimulus orienting (sec 0-5)	7 seconds	10%
Sustained attention (HR deceleration)	7 seconds	10%
Attention termination (return of HR to prestimulus level)	3 seconds	60%

FIGURE 6. Schematic illustration and typical results using on–line evaluation of heart rate to measure attention phases with the "interrupted stimulus paradigm." The peripheral stimulus delay is defined by time (preattention, stimulus orienting) or by on-line evaluation of heart–rate changes (sustained attention, attention termination).

peripheral stimulus was presented for a limited duration (e.g., 2 seconds), the infant did not localize the peripheral stimulus during stimulus orienting or sustained attention, but localized it very quickly during preattention and attention termination (Richards, 1991). The lack of distractibility by the peripheral stimulus during stimulus orienting and sustained attention indicates that attention was actively directed toward the centrally located stimulus. The ease with which distraction by the peripheral stimulus occurred during preattention and attention termination indicates that attention was no longer engaged by the central stimulus.

The findings from these studies show both developmental changes and individual differences in sustained attention. First, there were developmental changes in this age range in sustained attention but not in the other phases. For example, the level of the initial HR change during stimulus orienting was approximately 8 to 10 bpm across the age range from 8 weeks to 6 months of age (Richards, 1985, 1989b). The HR change during sustained attention increased across this age range, with the older infants (6-month-olds) showing sustained HR responding as long as they viewed the central stimulus (especially, Richards, 1985, Fig. 1; also see Table 1a). Second, HR changes and behavior in sustained attention showed reliable individual differences. On one level, this may be seen by correlations of around 0.4 or 0.5 between HR or fixation responses during sustained attention, between the ages of 3 and 4.5 months, and 4.5 and 6 months (Richards, 1989a, 1994). The individual differences are also shown by the strong relation between HR changes in sustained attention and HR variability due to respiration (RSA; respiratory sinus arrhythmia) in these age ranges. Across the age ranges from 3 to 6 months, the HR response during sustained attention is larger for infants with high levels of RSA than those with low RSA (Table 1b). RSA itself has a strong stability over this age range (Izard et al., 1991; Richards, 1989a, 1994). The relation between RSA and sustained attention appears to be due to fluctuations in RSA that occur as a result of development (Table 1c), and the corresponding close association of RSA and sustained attention at each age (Richards, 1989a, 1994; Richards & Casey, 1992). The individual differences and developmental changes are also paralleled by patterns of attention found in abnormally developing infants (see section 3.3).

A model of the attention-linked HR changes has been proposed by Richards and Casey (1992). It is supposed in this model that the HR changes are controlled by a widespread arousal system involving the mesencephalic reticular formation, limbic system, and frontal lobes. HR is an index of this system's activity, and HR changes during attention reflect this system's dual influence on cortical systems involved in attention and midbrain and brainstem systems involved in HR control. Developmental changes occur from birth through age six months in this system itself, as well as in this system's influence over the rapidly developing cortical areas involved in cognitively controlled attention. The increasing HR changes found in sustained attention from 2 to 6 months of age are a result of the development of this system, the development of this system's role in invigorating neural systems involved in attention, and the increasing level of integration between this nonspecific arousal system and attention systems that act specifically on cognitive operations. The developmental changes in the attention system parallel development in the neural systems controlling attention, fixation, and eye movement (e.g., Johnson, 1990). The integration between the arousal system and the systems controlling eye movement results in increasingly integrated brain-fixation-HR responses on the part of the developing infant.

TABLE 1

Table 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

Table 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

Table 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

Table 1d: *HR during sustained attention, and baseline RSA, low risk preterm infants from 3 to 6 months of age*

	14 weeks	20 weeks	26 weeks
Baseline RSA	0.14	0.17	0.49
HR during sustained attention	−2.22	−3.90	−4.22

Table 1e: *HR during sustained attention, and baseline RSA, in preterm infants with Respiratory Distress Syndrome from 3 to 6 months of age*

	14 weeks	20 weeks	26 weeks
Baseline	−0.14	−0.20	−0.67
HR during sustained attention	−2.80	−2.49	−1.89

Source: Richards, 1985; 1987; 1989a,b; 1994.

3.3. *Implications for Abnormal Development*

There have been many studies using HR of infant cognitive-psychophysiological development with abnormal children. And, unlike that with EEG/ERP, this work has been with research paradigms of interest to infant cognitive psychophysiology. This work has been reviewed in places such as W. Berg and K. Berg (1987), Fox and Fitzgerald (1990) and Von Bargen (1983).

An example of a study of sustained attention in high-risk preterm infants was done by Richards (1994). HR variability (such as RSA) is lower in preterm infants with severe respiratory difficulty than in low-risk preterm infants, or full-term infants (Kero, 1973; Fox, 1983; Rother et al., 1987). The HR responses of preterm infants are smaller or abnormal in response to psychological stimuli and situations (e.g., Fox & Lewis, 1983). A recent study by Richards (1994) found that HR responses of preterm infants during sustained attention were markedly different from low-risk preterm infants, or full-term infants. The infants were tested at 3, 4.5, and 6 months "conceptional" age, (e.g., gestational age + postnatal age). They were presented with an interesting visual stimulus on a TV monitor. As in previous studies with full-term infants (Richards, 1987, 1989a), the infant's HR was evaluated on-line for changes indicating stimulus orienting, sustained attention, and attention termination. The attention phases defined by HR were related to the distractibility of the infants to a peripheral visual stimulus.

There were two findings in this study of relevance to abnormal attention development. First, as in previous studies, level of RSA (HR variability) in a baseline recording was related to level of HR responding in the attention task. Figure 7 shows the HR changes in sustained attention for infants with high RSA relative to full-term infants, low RSA relative to full-term infants, and very-low-RSA infants found only in preterm groups. It can be seen that there was an increasing responsiveness of HR during sustained attention as the level of RSA increased. The very-low-RSA infants had HR responses that returned to prestimulus levels by about 5 or 6 seconds, whereas the other two groups had a sustained HR response during this time. The second finding was that low-risk preterm infants showed smaller HR responses in sustained attention, but had the same pattern of RSA increases and sustained attention increases found in full-term infants (Table 1d). High-risk preterm infants, those with respiratory distress syndrome at birth, had diminished HR responses in sustained attention, diminished levels of RSA, and no change in the diminished HR response or RSA levels over this age range (Table 1e). The attention deficit that was found in low-risk infants began to change as the infants became older, similar to full-term infants. The "deficit" found in the high-risk infants continued to exist over the entire age range.

The study of abnormal infant development with HR and cognitive tasks would serve a purpose similar to that outlined earlier with ERP. Damage to a CNS system caused by prenatal or perinatal events might be detected by psychophysiological tasks using HR or ERP measures. In some cases one measure might be specifically related to the perinatal event. For example, it is known that respiratory distress syndrome results in diminished HR variability, so one might expect abnormal cognitive behavior in infants in psychophysiological tasks using HR, but maybe not ERP's. This may be especially true in tasks designed to measure sustained attention, which is closely related to HR changes and HR variability in normal infants. On the other hand, if the CNS areas controlling attention were not affected, but those controlling visual association were, then one might expect the ERP measures taken during recognition memory to show abnormal patterns in infants, rather than HR measures. In both cases, or in cases where both HR and ERP were abnormal, the psychophysiological tasks that evaluate cognitive activity would be inherently more useful in identifying abnormal cognitive behavior in infants than psychophysiological tasks that evaluate simple sensory system.

4. *Summary and Conclusions*

This chapter reviewed two areas of infant cognitive psychophysiology. Both were chosen because they measured psychologically relevant physiological responses that occurred synchronously with psychological processes. Both of these areas showed developmental changes in the relation between the physiological measure and the psychological response.

There were several areas of infant cognitive psychophysiology that were not mentioned. Two in particular may be of interest. One area that has received a lot of attention is the relation between "spontaneous" or baseline physiological recordings, and psychological processing. The most relevant of these show parallel developmental changes in the physiology and the psychology, leading to the inference that the physiological changes underlie the psychological development. An example of a study of this type was reported by Bell and Fox (1992). They measured spontaneous EEG power in the frontal scalp regions, as well as coherence between the frontal brain region and other scalp regions. The EEG power and coherence, and its development, was presumed to show the maturity of the frontal brain area. They reported that infants at 12 months of age who

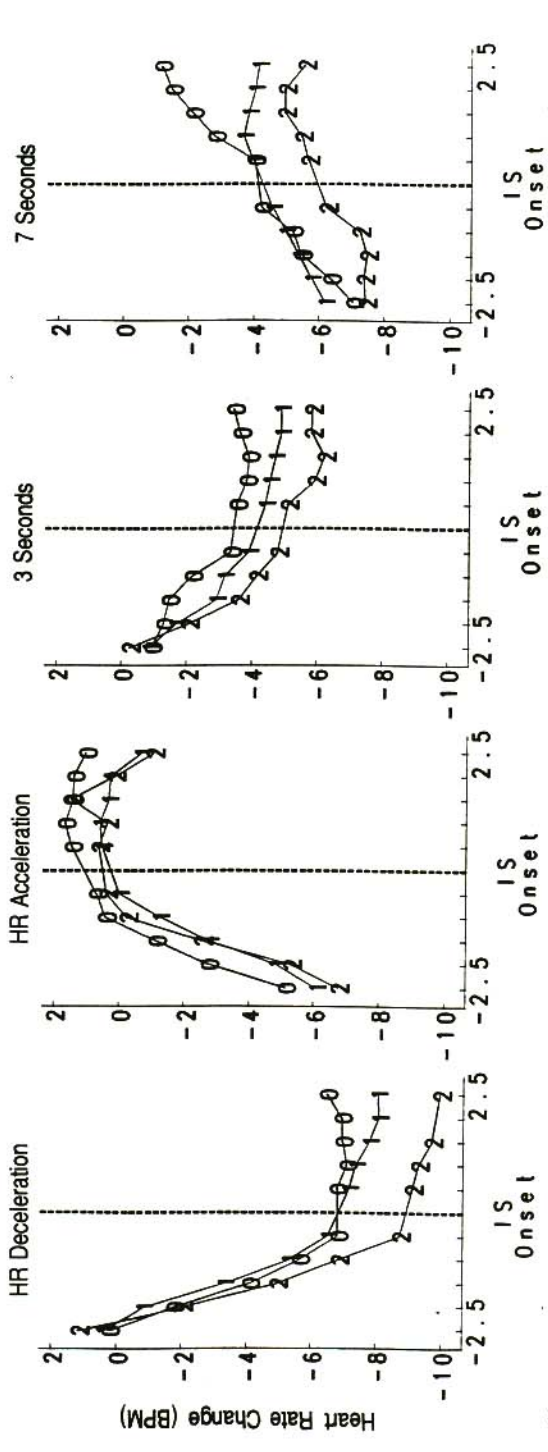


FIGURE 7. Mean heart-rate change preceding and following the interrupting stimulus onset for four interrupted-stimulus procedures, separately for pre- and full-term infants with high RSA (symbol: 2), pre- and full-term infants with low RSA relative to the full-term group (symbol: 1), and for preterm infants with very low RSA (symbol: 0). Reprinted by permision from Richards, 1994. Copyright 1994 Society for Psychophysiological Research.

successfully performed Piaget's object concept task with long levels of delay between exposure and test showed significant increases in frontal EEG power, and had larger coherence between the frontal and occipital brain regions. They proposed that the frontal region integrates representational memory with behavior control of response inhibition during the object concept task. Those with mature developmental patterns in EEG activity and interhemispheric coherence perform best on this task requiring frontal brain activity. In the Bell and Fox (1992) study, EEG/ERP was not measured at the same time as the cognitive behavior. Thus, the inferences about the brain–behavior relations exposed by the EEG measurements must be indirect. Such studies might be reasonably linked with ERP studies to show that concurrent brain activity, synchronous with the cognitive systems underlying the behavior, might be done in scalp areas recorded by these investigators.

There also have been many HR studies of developmental changes in baseline or spontaneous HR, and the relation of those changes to psychological development in the infant. One area that has received a lot of recent study is respiratory sinus arrhythmia (RSA) in HR. RSA is variability in HR that occurs at the same frequency as respiration. It is controlled by the brainstem areas involved in respiratory control, is affected by coordination in higher CNS cardiovascular centers, and is directly controlled at the efferent connections to the heart by the vagus nerve. This chapter has described some studies showing how baseline RSA changes over various ages were related to infant sustained attention (e.g., Richards, 1987, 1989, 1994; see Table 1). RSA has also been shown to be related to infant recognition memory (Linnemeyer & Porges, 1986; Richards & Casey, 1990), and several aspects of personality, temperament, stress, and reactivity in infants (Fox, 1989; Fox & Fitzgerald, 1990; Porges, 1991). RSA is also related to general developmental level (e.g., Fox & Porges, 1985; Richards & Cameron, 1989; Izard et al., 1991), and RSA level predicts later developmental outcome (Fox & Porges, 1985). As with the spontaneous EEG/ERP measures, the inference of causal relations between RSA and psychological behavior is indirect and must be made based on their close developmental association. However, developmental studies of HR during sustained attention, and RSA during baseline, have an advantage because the HR changes during attention are known to be controlled by the vagus nerve (e.g., Richards & Casey, 1991), the same system that controls RSA. Thus the close RSA/sustained attention relation across ages has a more direct connection, allowing stronger causal inferences.

The developmental changes in HR response, the developmental changes in ERP during the oddball paradigm, and the changes in spontaneous HR (e.g., RSA) and EEG suggests that an integration of the HR and

EEG/ERP measures may be possible. Infant attention and recognition memory are closely linked from the ages of 3 to 12 months. Changes in the selective and information processing aspects of attention are at least partially responsible for the increases in recognition memory over this age range (Richards & Casey, 1990). The attention-HR and the recognition memory-ERP associations, along with the attention–recognition memory link, suggest that an integrative research strategy using evoked HR and ERP, and attention and recognition memory, would be fruitful in studying infant cognitive-psychophysiological development. The developmental changes in spontaneous EEG patterns and HR patterns (e.g., RSA) also may be multiple indicators of widespread cognitive changes in the infant in the first year. Such a research strategy might emphasize a common paradigm or behavior, while looking at the developmental manifestations of this in the various physiological domains. This research strategy also could be used to characterize patterns of abnormal recognition memory in young infants when the abnormality is caused by specific CNS deficits. Perinatal insults that affect recognition memory (e.g., Gunderson, Grant, Burbacher, Fagan, & Mottet, 1986; Jacobson, Fein, Jacobson, Schwartz, & Dowler, 1985) may operate via CNS damage that could be detected in psychophysiological studies of recognition memory.

A more sophisticated systems view of psychophysiological development is needed in the infant ERP work. Such questions as where is it generated, how those areas develop, and why is it related to significant psychological development, should be answered. Studies of the source generators of these ERP components (e.g., Scherg, 1990; Scherg & Picton, 1991) would be useful in identifying the locations in the brain of the endogenous ERP components studied in infant recognition memory. More sophisticated models of brain development and psychological development and their integration in psychophysiological recordings are necessary. The models of HR change and development, and psychophysiological relations of HR, RSA, and attention (Richards & Casey, 1992; Porges, 1992; Berg & Donahue, 1992) have more sophisticated models of brain-controlled, psychologically relevant HR change than do analogous review chapters dealing with EEG and ERP (e.g., Vaughan & Kurtzberg, 1992; Nelson, 1993).

This basic research in infant cognitive psychophysiology has enormous potential for the study of abnormal infant development. On one hand, the spontaneous-EEG and the exogenous-ERP work have already shown the contribution of measurable brain functioning on the assessment of concurrent infant psychopathology. The prediction of psychological developmental outcome with early measures of physiological functioning

has been successful. One deficiency in this area is the evaluation of psychological processes concurrently with ERP activity in young infants. Whereas this work has been successful when dealing with abnormality or psychopathology in older children (e.g., Courchesne & Yeung-Courchesne, 1988), it has not been done with infant abnormal development. The evaluation of ERP with concurrent cognitive processes in young infants would aid the study of abnormal development by identifying the locus of the effects of early risk factors. It also should help in examining the disruption that occurs in higher order cognitive processes in high-risk infants (e.g., recognition memory, sustained attention, object concept), with a view to identification of children who are at risk for abnormal cognitive or intellectual functioning in the preschool and school years.

The work with HR, particularly evoked HR changes in psychological situations, has been more extensive than that with ERP. This work could be profitably expanded with more recent models of infant cognitive-psychophysiological development that has a reasonable theoretical model for the underlying brain systems that are developing (e.g., Johnson, 1990; Richards & Casey, 1992). These theoretical models hypothesize that normal infant psychological development results from changes in brain systems and the increasing integration/specialization of brain systems over the first year of life. Abnormal infant development could conceivably occur because of abnormal development in these brain systems. For example, the study with high-risk premature infants presented earlier (Richards, 1994) showed that the continuing deficit in the HR responses during sustained attention was a result of the continuing, abnormally low RSA level in the high-risk infants. This, in turn, must be related to the brain systems controlling RSA, and may have more wide-ranging implications for high-risk infant development because of the association of RSA with other psychological behaviors. With models like these, the conditions in infancy that lead to abnormal psychological development (e.g., prematurity with respiratory problems, genetic abnormalities, teratogens) could be characterized more precisely, and the nature of the effects better specified, with the more sophisticated models of brain-behavior development found in these infant cognitive-psychophysiological models.

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