22 Attention in Young Infants: A Developmental Psychophysiological Perspective

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ABSTRACT This chapter reviews the development of attention in young infants, emphasizing heart rate changes in psychophysiological experiments as a measure of an arousal brain system. The neural systems affecting attention that may be indexed by psychophysiological measures are briefly reviewed. Heart rate, electroencephalogram (EEG), event-related potentials (ERP), and other physiological measures are reviewed that have been used for the study of attention development in young infants. The developmental changes in infant attention are related to changes occurring in the neural systems underlying attention. Several studies are reviewed that show how heart rate may be used as a measure of a general arousal system in young infants.

Attention, generally defined, shows dramatic development over the period of infancy. At birth infants attend primarily to salient physical characteristics of their environment or attend with nonspecific orienting (Berg and Richards, 1997). Between birth and two years the development of alert, vigilant sustained attention occurs. At the end of the first two years, infants' executive attention system is beginning to function (Ruff and Rothbart, 1996; also see Rothbart and Posner, this volume). These dramatic changes in infants are commonly thought to be based predominantly on age-related changes in brain structures responsible for attention control.

This chapter has three objectives. First, brain systems that may be involved in attention and show development in infancy are reviewed. These systems include a general arousal system that affects many cognitive functions as well as specific attention systems that are limited in their effect on cognition and attention. Second, psychophysiological measures that have been useful in the study of brain–attention relations in infants are presented. The use of heart rate as a measure of the general arousal system is emphasized. Finally, several studies are examined that used these psychophysiological methods to study the development of infant attention. This review is limited to the use of heart rate as an index of the development of sustained attention, which is a general arousal system affecting a wide number of behavioral and cognitive functions controlled by the brain. These experiments are related to changes occurring in the neural systems underlying attention.

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Brain systems involved in attention

AROUSAL ATTENTION SYSTEM One emphasis in the cognitive neuroscience of attention has been on the arousal associated with energized cognitive activity (Posner, 1995). The arousal emphasis has focused upon the increased behavioral performance that occurs when attention is engaged. This increased behavioral performance is associated with shortening of reaction times in detection tasks, increased focus of performance on specific tasks, and the sustaining of performance over extended periods of time. The arousal emphasis is nonspecific, affecting multiple modalities, cognitive systems, and cognitive processes. This arousal emphasis characterizes attention's energizing effect on cognitive and behavioral performance. Attention also may have a selective effect on specific cognitive processes or behavior without arousal properties. In fact, selective attention may serve in some situations to inhibit behavior if such inhibition is appropriate for the goal of the task.

Specific locations or systems in the brain control the arousal aspect of attention. The brain systems underlying the arousal aspect of attention have been detailed in the theoretical and empirical research literature for a number of years. An example of this arousal emphasis is a model of neuroanatomical connections between the mesencephalic reticular activating system and the cortex (Heilman et al., 1987; Mesulam, 1983). This model (diagrammed in figure 22.1) presumes that there are centers broadly scattered throughout the mesencephalic reticular activating system that are activated by sensory stimulation. In turn, the mesencephalic

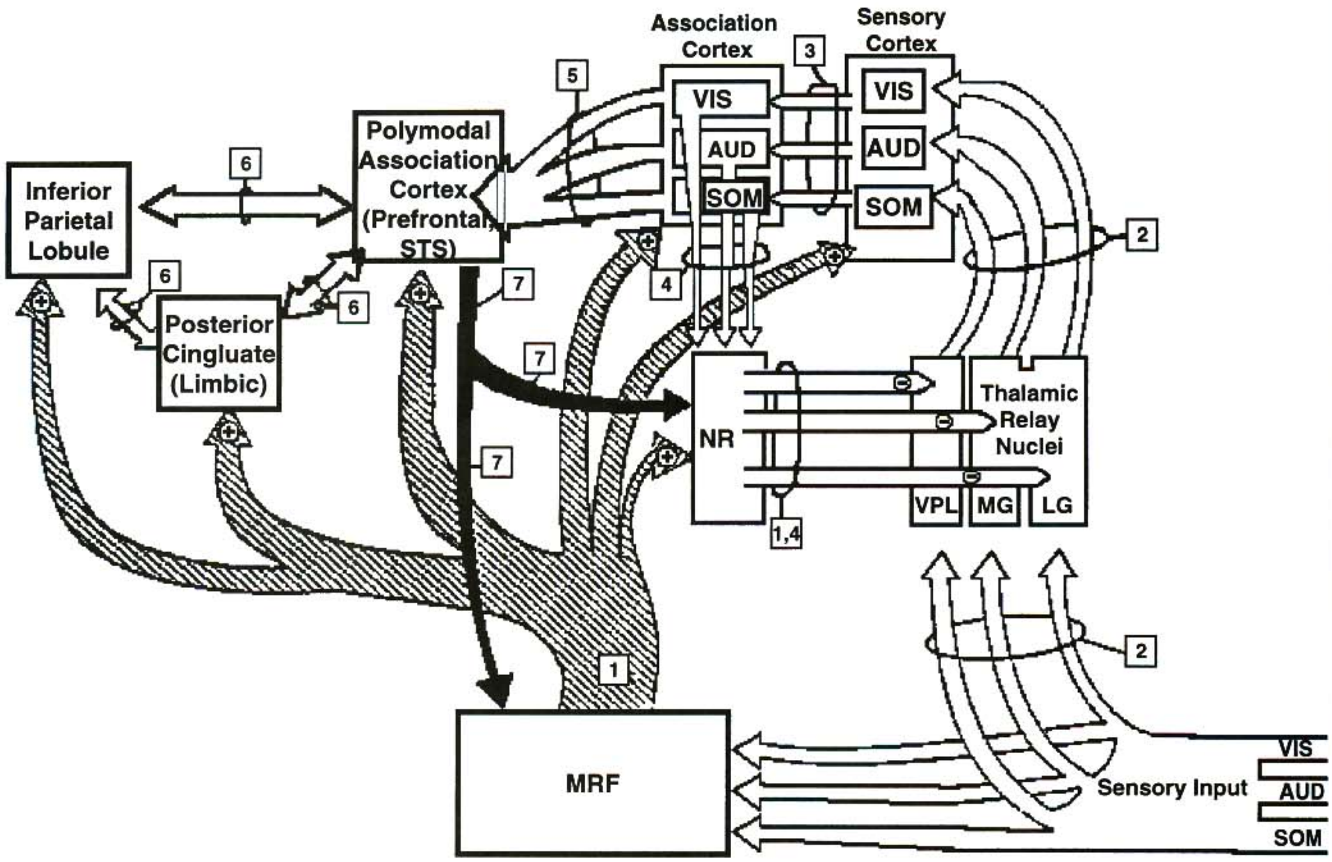

FIGURE 22.1 The arousal system of the brain. (1) Polysynaptic reticulocortical pathways; (2) sensory transmission; (3) associative cortex projections; (4) unimodal projections to reticular nucleus of the thalamus (NR); (5) sensory convergence to polymodal cortex; (6) supramodal cortex (inferior parietal lobule); (7) cortical arousal through mesencephalic reticular formation (MRF) and NR. STS, superior temporal sulcus; VIS, visual; AUD, auditory; SOM, somatosensory; VPL, ventralis posterolateralis; MG, medial geniculate; LG, lateral geniculate. (Copyright 1981, American Medical Association. Reprinted with permission from Watson, R. T., E. Valenstein, and K. M. Heilman 1981. Thalamic neglect: Possible role of the medial thalamus and nucleus reticularis in behavior. *Arch. Neurol.* 38:501–506.)

reticular activating system directly influences the limbic system, thalamus, and cortex. The cingulate cortex receives information from areas of the limbic system such as the basolateral nucleus of the amygdala and the subicular portion of the hippocampus. The cingulate cortex is a major afferent relay center that projects to parietal area PG, visual association cortical areas, and other cerebral cortex centers involved in complex cognitive functions. This neuroanatomical system acts in synchrony to "energize" primary sensory areas in the cortex and increase the efficiency of responding in those areas. This system also influences association areas and other attention systems, such as the posterior attention system described by Posner (Posner, 1995; Posner and Petersen, 1990). The nonspecificity of this system is implied by its interconnections with multiple areas that influence cognitive processing. This arousal system "invigorates" or "energizes" cognitive processes, leading to increased processing efficiency, shorter reaction times, better detection, and sustaining of cognitive performance for extended periods of time.

Another perspective on the arousal aspect of attention is a model based on the neurochemical systems involved in arousal. Robbins and Everitt (1995) distinguish four neurochemical systems that form the basis for the arousal functions of attention: noradrenergic, cholinergic, dopaminergic, and serotoninergic. Figure 22.2 (see color plate 14) shows the projections from midbrain nuclei for these four brain systems. The nuclei that give rise to these four neurochemical systems are located in brain regions adjacent to the mesencephalic reticular activating system. Robbins and Everitt (1995) review the evidence linking these neurochemical projection systems to attention and arousal. The noradrenergic and cholinergic systems are thought to be the neurochemical systems that are most closely involved in cortical arousal as it is related to attention. The dopaminergic system affects the motivational and energetic

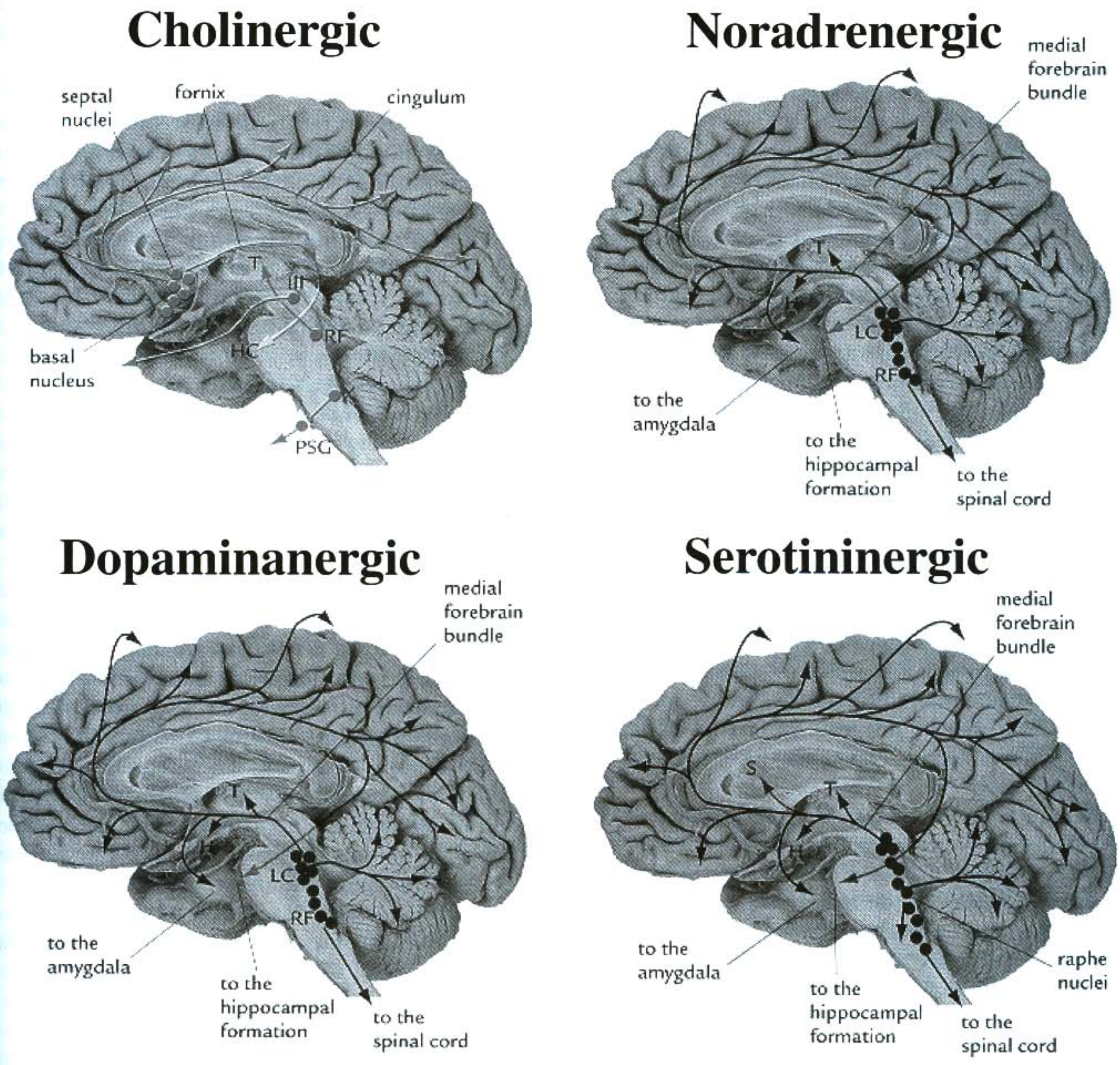

FIGURE 22.2 The neurochemical systems involved in attention and arousal. *Abbreviations:* III, oculomotor nucleus; T, thalamus; HC, hippocampal formation; RF, reticular formation; PSG, parasympathetic ganglion cell; X, dorsal motor nucleus of the vagus; H, hypothalamus; LC, locus ceruleus; C, caudate nucleus; P, putamen; S, septal nuclei; V, ventral striatum. (Reprinted with permission from Nolte, J., and J. B. Angevine, 1995. *The Human Brain.* St. Louis, MO: Mosby.)

aspects of cognitive processing and the serotonin system affects the overall control of state. These four neurochemical systems are closely linked so that more than one is likely to be operating during an aroused state.

SELECTIVE ATTENTION The second manner in which the brain affects the development of attention in infants is found in brain systems specific to selected functions. These brain areas show enhanced functioning under attention but affect only a single (or few) cognitive functions. Therefore, these systems have only a narrow and selective impact on attention-based cognitive functioning. Two of these are worth mentioning in this respect. The enhancement of visual receptive fields during attention to visual stimuli has been widely studied in invasive preparations (Desimone and Duncan, 1995; Maunsell and Ferrera, 1995). This type of attention is selective for particular objects, particular spatial locations, or particular tasks. For example, the responses of visual receptive fields are enhanced in tasks requiring focused allocation of attention to that specific visual field or to objects occurring in that visual field. Objects occurring outside of that receptive field have unaffected responses when the field is irrelevant to the task, or may have attenuated responses if the object occurring in that location interferes with task performance in the specific visual field. For neurons (or neural areas) that respond in this manner, this type of attentional modulation is specific to a limited number of cognitive aspects (e.g., a specific stimulus, modality, or task) and typically occurs in a very restricted portion of the brain (e.g., individual neurons or restricted brain areas).

There are single brain systems that are distributed over large areas but whose component neural subsystems operate in a functionally dedicated or specific manner. For example, the "posterior attention system" described by Posner (Posner, 1995; Posner and Petersen, 1990; see also Rothbart and Posner, this volume) involves the parietal cortex, pulvinar, superior colliculus, and perhaps, the frontal eye fields. This attentional network has a specific purpose—that of moving attention (visual attention?) around in space and localizing receptors (eyes?) to targets at specific locations. This attention system is not sensitive to specific targets, is unrelated to attention in stimulus modalities or cognitive functions that do not involve spatial localization, and does not enhance or attenuate other cognitive systems when it operates.

These specific brain systems show development in the period of infancy and are related to behavioral indices of infant attention that show development in the same time period. Such considerations may be found in the chapters by Johnson and by Rothbart and Posner in this volume and in other sources (e.g., see Johnson's eye movement–attention model; Johnson, 1990, 1995; Johnson, Gilmore, and Csibra, 1998; Johnson, Posner, and Rothbart, 1991). These specific attention systems are not covered extensively in this chapter.

Psychophysiological measures of infant attention

Psychophysiological measures are useful in the study of infant attention and infant brain development. Psychophysiology, which studies psychological processes using physiological measures, is focused on the psychological processes themselves as well as their relation to the processes affecting the physiological measures (Andreassi, 1989). The physiological measures used in psychophysiology are noninvasive and thus may be used with human participants such as infants. Additionally, most of these physiological measures are practical in psychological experiments. Recording equipment and sensors are nonintrusive and the sensors do not disrupt the infant's normal behavior patterns. The use of heart rate and EEG/ERP as psychophysiological measures of attention is reviewed briefly, exemplifying this approach.

HEART RATE Heart rate is the most common measure used by psychophysiologists who study young infants. The electrocardiogram (ECG) is measured with surface electrodes placed on the infant's chest, back, arms, or legs. Heart rate is derived from the ECG by measuring the interval between two "R-waves" of the ECG and is defined as the "inter-beat interval" (IBI; R–R Interval), or as the inverse of the IBI, heart rate (beats per minute, bpm). The infant's heart rate may be measured in response to psychological manipulations as a measure of attention .The infant's heart rate also may form the basis for determining if the infant is attending to a stimulus, and psychological manipulations are then made on the basis of the heart rate change (e.g., Richards, 1987). Heart rate may be used to distinguish general and specific forms of attention.

Richards (Berg and Richards, 1997; Richards, 1995; Richards and Casey, 1992; Richards and Hunter, 1998) has presented a model in which infants' heart rate changes during stimulus presentation are used to distinguish four attention phases: the automatic interrupt, the orienting response, sustained attention, and attention termination. Heart rate and attention level vary during these phases. Figure 22.3 schematically depicts the heart rate changes occurring during these phases of attention. This figure represents heart rate changes of infants from 3 to 6 months of age presented with a visual stimulus (Richards and Casey, 1991). The figure also has labeled a "preattention" phase and "preatten-

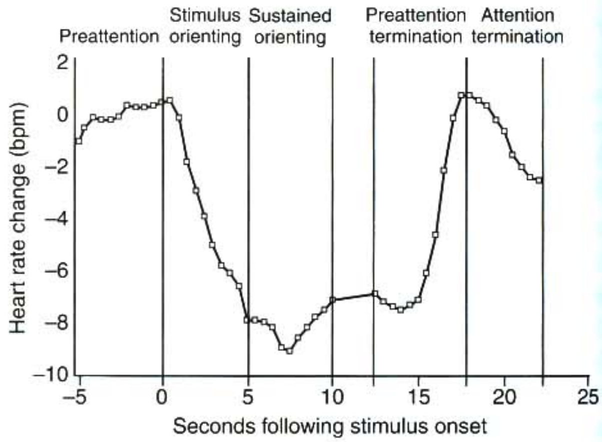

FIGURE 22.3 Average heart rate change as a function of stimulus following stimulus onset for the heart rate defined attention phases for infants from 3 to 6 months of age. (From Richards and Casey, 1991.)

tion termination" phase. These periods are simply the period of time before the presentation of the stimulus (preattention) and before heart rate returns to its prestimulus level but after sustained attention has occurred (preattention termination).

Sustained attention and attention termination affect a wide range of cognitive functions in infants. The heart rate slows down and remains below prestimulus levels during sustained attention. Cognitively, this phase of attention involves subject-controlled processing of stimulus information. Sustained attention is accompanied behaviorally by maintaining fixation on a focal stimulus in the presence of a peripheral distracting stimulus (Hicks and Richards, 1998; Hunter and Richards, 1997; Lansink and Richards, 1997; Richards, 1987, 1997a), acquiring stimulus information (Richards, 1997b) and exhibiting recognition memory (Richards and Casey, 1990), and enhancement of responses in a selected stimulus modality and inhibition of responses in a nonselected stimulus modality (Richards, 1998, 2000a). Alternatively, at the end of sustained attention the heart rate returns to its prestimulus level and the phase of attention termination occurs. Attention termination is accompanied by inattentiveness toward the stimulus in the presence of continued fixation on the stimulus, i.e., heightened levels of distractibility, lack of acquisition of stimulus information, and lack of selective modality effects.

The arousal system of the brain controls the heart rate changes that occur during sustained attention. The neural control of this heart rate change originates from cardioinhibitory centers in the orbitofrontal cortex. This area has reciprocal connections with the limbic system and through these connections is involved in modulating activity within the mesencephalic reticular formation arousal system (Heilman et al., 1987; Mesulam, 1983) and probably the dopaminergic and cholinergic neurotransmitter systems (Robbins and Everitt, 1995). The cardioinhibitory centers act through the parasympathetic nervous system to slow heart rate when the arousal system is engaged. This slowing of heart rate occurs as "vagus nerve" (10th cranial nerve) activity increases, leading to a slowing of the cardiac pacemaker firing, increases in interbeat intervals, and heart rate slowing. The "arousal" system does not result in more activity in heart rate, but inhibited activity. Similarly, some other peripheral physiological processes (e.g., body movement) are inhibited during conditions of attentive arousal. Thus, the arousal brain system when operating in this arousal-attention manner selectively enhances some brain systems and functions while inhibiting others.

The phases of sustained attention and attention termination are markers of the nonspecific arousal system of the brain (Richards and Casey, 1992; Richards and Hunter, 1998). This nonspecific arousal system sustains attention and maintains a vigilant state. The heart rate changes occurring during sustained attention (sustained heart rate slowing) index the onset and continuing presence of this arousal. The heart rate changes during attention termination (return of heart rate to its prestimulus level) index the lack of activation of this arousal system. These two phases of attention therefore reflect the nonspecific arousal that may affect a number of sensory and brain systems. Incidentally, these phases and the "automatic interrupt" and "stimulus orienting" attention phases also may be used to measure specific attentional systems in the young infant (e.g., Balaban, 1996; Berg and Richards, 1997; Richards, 1998, 2000a).

The heart rate changes occurring during attention and their indexing of arousal brain systems are important for developmental cognitive neuroscience because these heart rate changes show important developmental changes in the first six months of infancy. A consistent pattern of developmental changes has been shown to occur in the sustained attention phase. The level of the heart rate deceleration during sustained attention increases from 14 to 26 weeks of age (3 to 6 months) (Casey and Richards, 1988; Richards, 1985, 1987, 1989a,b, 1994). The level of heart rate during sustained attention is thought to reflect the depth of the arousal. Thus, the changes in the evoked heart rate response during sustained attention imply that the arousal controlled by the brain is increasing over this age range.

The age change in heart rate during sustained attention parallels some of the behavioral manifestations of attention. This includes an increasing ability of infants to acquire familiarity with stimulus characteristics in a fixed period of time (Frick and Richards, 2001; Richards, 1997b), enhanced tracking of moving stimuli (Richards and Holley, 1999), and the selective modality enhancement effect found in selective attention (Richards, 1998, 2000a). The behavioral and heart rate indices of attention are not as well synchronized at younger ages (e.g., 8 weeks) as they are at older ages (Hicks and Richards, 1998; Hunter and Richards, 1999, 2000; Richards, 1989b). The age-related changes in heart rate during sustained attention, and these age changes in the tasks corresponding to sustained attention, imply that this general arousal system develops in the first few months of infancy and that it increasingly affects infants' cognitive behavior.

Other Psychophysiological Measures There are other psychophysiological measures that have been used in the study of infant attention and its development. Although not reviewed extensively in this chapter, two in particular are worth mentioning: the electroencephalogram (EEG) and scalp-recorded event-related-potentials (ERPs). Spontaneous electrical activity of very small magnitude may be recorded from the human scalp. This activity is termed the "electroencephalogram" (EEG). Scalp EEG consists of continuous voltage changes that are caused by action potentials summed over large numbers of neurons, synapses, or neural pathways. This activity in the brain comes primarily from activity in the cerebral cortex and thalamocortical connections and so measures activity in the cerebral cortex. The EEG has been used in adults as a measure of nonspecific arousal (e.g., Ray, 1990) and occasionally in infants as a measure of arousal during task performance (e.g., see Bell, 1998). This measure could be useful for a relatively direct measure of cortical activity (though it cannot be easily linked to specific cortical areas). However, EEG has not been used frequently in the context of infant attention development. This chapter does not review the developmental changes occurring in EEG, but the reader may refer to other sources (e.g., Bell, 1998, 1999; Bell and Fox, 1992, 1994; Berg and Berg, 1987).

Scalp-recorded event-related-potentials (ERPs) are derived from the EEG recording. The EEG may be time-locked to specific experimental events and averaged over multiple trials, resulting in averaged ERPs. The ERP has varying positive and negative electrical waves that are referred to as "components." These components are hypothesized to be caused by specific cortical events, which are, in turn, hypothesized to be closely related to psychological processes. These components include those such as the P1 (or P100), N1, P2, N2, P3 (or P300), and various slow waves (for a discussion of these components in infants, see Nelson, 1994; Nelson and Dukette, 1998; or de Haan and Nelson, 1997; for a discussion of these components in adults, see Hillyard et al., 1995, or Swick, Kutas, and Neville, 1994).

The ERP is thought to reflect specific cognitive processes, and also may provide a noninvasive and direct measure of functioning within specific brain areas (see Hillyard et al., 1995). For example, specific components of the ERP change in response to familiar and unfamiliar visual stimuli (Nelson and Collins, 1991, 1992). These authors demonstrated changes in the amplitudes and latencies of specific ERP components in response to visually presented novel stimuli. Likewise, the ERP may be used to index specific attentional responses. One such measure is the Nc (negative central) component (Courchesne, 1977, 1978) which is thought to represent a relatively automatic alerting response to the presence of a visual stimulus, especially a novel stimulus (cf. heart-rate–defined "stimulus orienting," Richards and Casey, 1992; see also Recognition of Briefly Presented Visual Stimuli). The ERP has been used extensively in infant participants, and many reviews of this measure are available (Berg and Berg, 1987; Nelson, 1994; Nelson and Dukette, 1998; see also Nelson and Monk, this volume; Johnson, Mareschal, and Csibra, this volume).

Psychophysiological Measures as "Marker Tasks"

Some comments should be made on the nature of the psychophysiological measures as direct or indirect measures of brain activity. Many psychophysiological measures are indirect measures of brain activity. Heart rate as an index of a general arousal system in the brain should be considered an indirect measure. The connections between the mesencephalic reticular activating system, its associated attention-arousal system (Heilman et al., 1987; Mesulam, 1983), and heart rate control are well known. Also, the connection between the neurochemical arousal systems (Robbins and Everitt, 1995) and cardiac control are known. But the measurement of such brain systems is indirect when using heart rate as a psychophysiological measure of infant attention. The EEG is an indirect measure of such a brain system when used to measure arousal.

The indirect measure of brain activity with psychophysiological measures is similar to the "marker task" concept detailed by Johnson (1997). Marker tasks are behavioral tasks that have been studied in animal or invasive preparations and are controlled by specific brain areas or systems. Johnson (1997) proposes that such tasks may be used in infants and children with the understanding that developmental changes in these tasks should reflect developmental changes in the brain areas that control their functioning. In the case of behavioral marker tasks or psychophysiological measures, a solid theoretical or empirical basis for relating the measure to a brain system or controlling brain functions is necessary. The study of attention further requires that these brain systems be related to common attention functions (arousal, selection). Finally, the psychophysiological measures, or the behavioral tasks, should be used in experimental situations in which relevant psychological processes affect the physiological system (or behavioral marker task). The indirect psychophysiological measures (and behavioral marker tasks) allow inferences to be made about brain development and help to inform a developmental cognitive neuroscience approach to attention.

Some psychophysiological indices reflect brain activity more directly. The EEG and ERP are direct measures of brain function in some contexts. For example, auditory brainstem-evoked potentials are derived from highly filtered, event-averaged EEG. These brainstem-evoked potentials are generated at specific points in the neural pathway from the peripheral auditory apparatus through the auditory nerves to the brainstem. They measure functioning of these pathways in a direct sense. Similarly, some cortical ERP measures may be similarly interpreted using high-density recording (Tucker, 1993; Tucker et al., 1994), and cortical sources may be hypothesized and compared with the scalp distribution of the ERP components (Nunez, 1990; Scherg, 1990; Scherg and Picton, 1991). Functioning of the cortical areas may be inferred from these cortical source localization procedures in a direct fashion. The use of the ERP and cortical source localization procedures as a direct measure in the study of attention is only beginning with infant participants. Such use of the EEG and ERP should lead to a higher quality of information about the relation between the brain and attention in infant psychological development.

In the rest of the chapter we review studies that show the developmental changes that occur in the arousal form of attention. The first section reviews two studies (Richards, 1998, 2000a) that use modification of the blink reflex with selective attention. These studies show how a specific attention system interacts with the development of the general arousal system. Next we review a study (Richards and Holley, 1999) showing the effect of the developing arousal system on eye movements that themselves show development over the first six months in infancy. The final section of the reviews presents some studies that show developmental changes in sustained attention that are related to a "higher cognitive function," infants' recognition of briefly presented visual stimuli (Frick and Richards, 2001; Richards, 1997b, 2000b; Richards and Casey, 1990). These studies show that familiarization of patterns presented for only a few seconds during sustained attention results in recognition memory (Frick and Richards, 2001; Richards, 1997b). This section also presents some new, as yet unpublished data which show that during attentive states infants will recognize stimuli very quickly, exhibiting appropriate EEG and ERP changes associated with recognition memory (Richards, 2000b). These studies should be considered examples of how developmental psychophysiology may contribute to developmental cognitive neuroscience of attention.

Selective attentional modification of blink reflexes

Here we review studies showing the effect of selective attention on the blink reflex and examine how the development of the arousal attention system in young infants modulates this selective attention effect. The startle reflex is a response to high-intensity short-duration stimuli, and includes widespread flexor jerk and whole body startle. One aspect of the startle reflex is the startle blink reflex. The blink reflex occurs in response to visual, auditory, tactile, and other stimuli. The acoustic startle blink reflex and the visual startle blink reflex are based upon short-latency reflex pathways involving first-order neurons in the sensory pathways and the brainstem cranial nerves that move the muscles for the blink (Balaban, 1996; Davis, 1997; Hackley and Boelhouwer, 1997). The blink reflex represents an "automatic interrupt" system that interrupts ongoing information processing and shifts the organism's goals for other activities (Graham, 1979, 1992).

One characteristic of the blink reflex that has been of interest to cognitive psychophysiologists is its modifiability by selective attention. Directing attention to one stimulus modality enhances the blink reflex to a stimulus of that modality and attenuates the blink reflex to stimuli in other modalities (Anthony, 1991; Anthony and Graham, 1983, 1985; Balaban, Anthony, and Graham, 1989; Hackley and Graham, 1983; Haerich, 1994; Richards, 1998, 2000a). This attentional modulation shows that a higher-order cognitive process, selective attention to a specific modality, may modify reflexes controlled by simple reflex arcs in the central nervous system. This attenuation/modification of the blink reflex also may be used as an index of the amount of higher-order selective attention. The modality-selective effect of attention on the blink reflex has been shown in young infants (Anthony and Graham, 1983; Balaban, Anthony, and Graham, 1989; Richards, 1998, 2000a).

Two recent studies used heart rate changes associated with the arousal aspect of attention to show developmental changes in the selective modality effect on the blink reflex (Richards, 1998, 2000a). In these studies, infants at 8, 14, 20, or 26 weeks of age were presented in the foreground with interesting visual or auditory stimuli (Richards, 1998) or a multimodal auditory-visual stimulus (Richards, 2000a). The infant's heart rate was recorded and delays were defined according to heart rate changes associated with phases of attention. For example, "sustained attention" was defined as a significant heart rate deceleration beyond the prestimulus level, and "attention termination" was defined as a return of heart rate to its prestimulus level following a period of sustained attention. When it was thought that sustained attention was engaged, or attention was unengaged, an auditory or visual stimulus that elicits a blink reflex was presented. The amplitude of the blink reflex was measured and compared in the attentive (aroused) and inattentive (unaroused) conditions.

There were three results relevant to the present chapter. As expected from previous studies with adults and young infants, there was a selective modality effect on the blink reflex. Figure 22.4 (Richards, 1998) shows the blink reflex magnitude for attentive and inattentive conditions as a function of the match between the foreground stimulus and the blink reflex stimulus. During sustained attention the blink magnitude was larger when the foreground and blink reflex stimulus were in the same modality, and the blink magnitude was smaller when the modalities did not match. Alternatively, during attention termination this selective modality effect was not found. These effects were very similar when single modality foreground stimuli were used (Richards, 1998) or multimodal foreground stimuli were used (Richards, 2000a).

There was a developmental change in the level of the selective modality effect from 8 to 26 weeks of age in this study. Figure 22.5 (Richards, 1998) shows the difference between a prestimulus condition in which attention was not engaged and the modality-match and modality-mismatch conditions during sustained attention. Over these ages there was a clear increase in the enhancement of the blink reflex for the modality-match conditions and an increase in the attenuation of the blink reflex for the modality-mismatch conditions. This implies that the selective modality effect occurs primarily when the infants were highly aroused (sustained attention) but does not occur during lack of arousal or inattentiveness (attention termination).

There were no selective modality effects on heart rate itself, and the heart rate changes worked similarly in their enhancement/attenuation effects for auditory, visual, and multimodal auditory-visual stimuli. For example, the heart rate changes in response to the visual and auditory blink stimuli were the same regardless of the foreground stimulus to which attention was directed. This implies that the heart rate changes were indexing a general arousal system rather than one tied to a specific sensory modality or a specific attention system. This is consistent with the idea that the heart rate changes during sustained attention reflect the general arousal systems of the brain.

These studies show how a specific attention system interacts with the developing general arousal system of the brain. The heart rate changes that indicated sustained attention or attention termination are hypothesized to be an index of the general arousal system of the brain (Heilman et al., 1987; Mesulam, 1983; Robbins and Everitt, 1995). This general arousal system shows development over this period of infancy (i.e., 2–6 months). The blink reflex represents simple preatten-

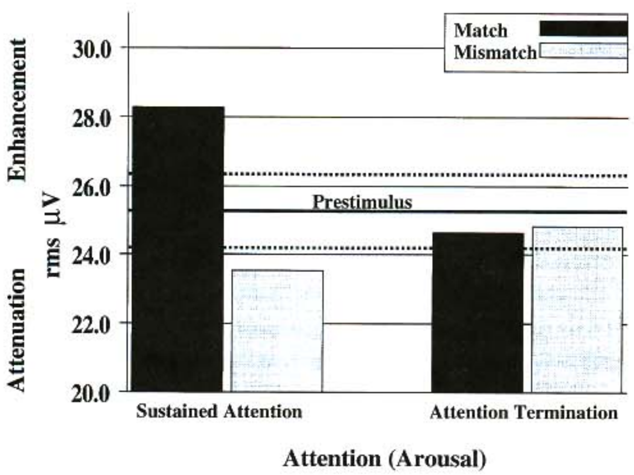

FIGURE 22.4 Blink reflex magnitude (rms, µV) as a function of the sustained attention or attention termination and the match/mismatch between the foreground and the blink stimulus. The solid black bars represent trials on which the foreground and the blink reflex stimuli were in the same modality, and the light bars represent trials on which the foreground and blink reflex stimuli were in different modalities. Also shown is the average blink magnitude on prestimulus trials with no foreground stimulus (solid line; SE ranges as dashed line). (Adapted from Richards, 1998.)

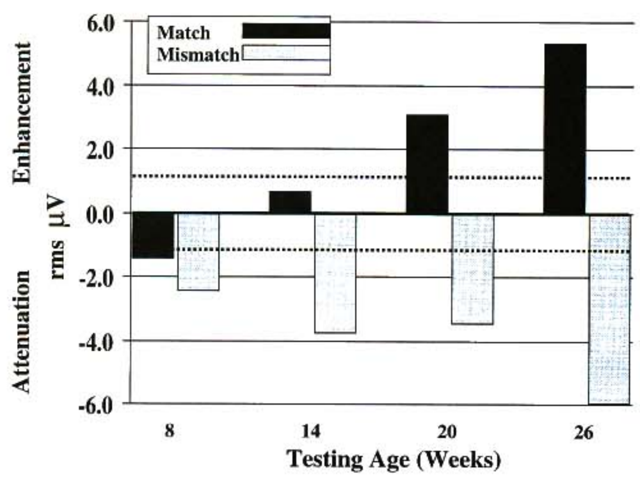

FIGURE 22.5 Blink reflex magnitude (rms, µV) difference from the prestimulus to the sustained attention conditions and the match/mismatch between the foreground and the blink stimulus, separately for the four testing ages. The solid black bars represent trials on which the foreground and the blink reflex stimuli were in the same modality, and the light bars represent trials on which the foreground and blink reflex stimuli were in different modalities. The SE for the prestimulus trials is shown as a dashed line around the 0 rms µV point. (Adapted from Richards, 1998.)

tive cognitive processes (e.g., "automatic interrupt"; see Graham, 1979, 1992) and is controlled by subcortical pathways and brain mechanisms. The spinal motor neurons controlling the blink muscles and the brainstem afferent pathways involved in the blink reflexes are relatively mature at birth (Balaban, 1996). Thus, the reflex itself shows little developmental change over the testing ages such as those used in this study. The development of sustained attention over this age range thus influences the extent to which selective attention will affect this low-level cognitive process. Over this age range there is an increasing influence of the general arousal system over this very specific attention system, both controlled by brain processes.

Visual smooth pursuit eye movements and attention

This section reviews the relation between the development of the arousal attention system in young infants and three eye movement control systems that show development in the same period of time. There are three types of eye movements that may be made when tracking visual stimuli. Each eye movement type is controlled by separate areas of the brain. *Reflexive saccadic* eye movements occur in response to the sudden onset of a peripheral stimulus. These eye movements are controlled by a brain pathway involving the retina, lateral geniculate nucleus, superior colliculus, and perhaps the primary visual area (Schiller, 1985, 1998). *Voluntary saccadic* eye movements occur under voluntary or planned control. These eye movements often involve attention-directed targeted eye movements. The voluntary saccadic eye movements are controlled by a brain pathway involving several parts of the cortex, visual areas 1, 2, and 4, the parietal cortex area PG, and the frontal eye fields (Schiller, 1985, 1998). *Smooth pursuit* eye movements represent a third type of eye movements used in tracking visual stimuli. These eye movements occur only in the presence of smoothly moving visual stimuli, and smoothly track visual stimuli over a wide range of visual space. Smooth pursuit eye movements also are controlled by brain pathways involving the cortex, including areas MT (medial temporal) and MST (middle superior temporal), and perhaps the parietal cortex (Schiller, 1985, 1998). The voluntary saccadic and smooth pursuit eye movements are affected by attention whereas reflexive saccadic eye movements are relatively independent of attention control.

Unlike the blink reflex, the brain areas involved in the control of these three eye movement systems undergo developmental changes in the first six months. There have been several models of the brain changes affecting eye movement development, including models by Bronson (1974, 1997), Maurer and Lewis (1979, 1991, 1998), Johnson and colleagues (Johnson, 1990, 1995; Johnson, Gilmore, and Csibra, 1991; Johnson, Posner, and Rothbart, 1998), Hood (Hood, 1995; Hood, Atkinson, and Braddick, 1998), and Richards (Richards and Casey, 1992; Richards and Hunter, 1998). A model proposed by Johnson (1990, 1995; Johnson, Gilmore, and Csibra, 1991; Johnson, Posner, and Rothbart, 1998) describes the developmental changes in these three eye movement systems. This model hypothesizes that layers of the primary visual area develop at different rates and become mature at different ages. The primary visual area layers containing brain pathways that control reflexive eye movement are relatively mature at birth, hence reflexive saccadic eye movements dominate the infant's behavior in the first 2 postnatal months. The primary visual area layers that contain brain pathways which control voluntary saccadic eye movements develop rapidly from the first to the sixth postnatal months. In conjunction with this development, attention-directed voluntary saccades show developmental changes over the first six months. Finally, the primary visual area layers that contain brain pathways which control smooth pursuit eye movements develop more slowly than the other layers. Several parts of the brain pathways that control smooth pursuit eye movements show protracted developmental changes over the first two years (Richards and Hunter, 1998). Thus, smooth pursuit eye movements are the latest to begin development and show changes over a longer period than just the first six months of infancy. Figure 22.6 (Richards and Hunter, 1998) shows a hypothetical developmental trend for these three eye movement systems.

Richards and Holley (1999) examined infants' tracking behavior over this age range under conditions of attention and inattention. Their study shows how the development of the general arousal system affects the exhibition of eye movements in the first six months of infancy. Infants at 8, 14, 20, and 26 weeks of age were presented with stimuli that moved at varying speeds (8–24 deg/s) on a television monitor. The infants' heart rate was recorded and periods of visual tracking were separated into attentive and inattentive states using the heart-rate–defined attention phases described earlier. The infants' eye movements were tracked with an electrooculogram (EOG) by recording electrical potential changes due to shifts in the eyes. The eye movements were separated into smooth pursuit and saccadic eye movements and related to the attentiveness of the infant.

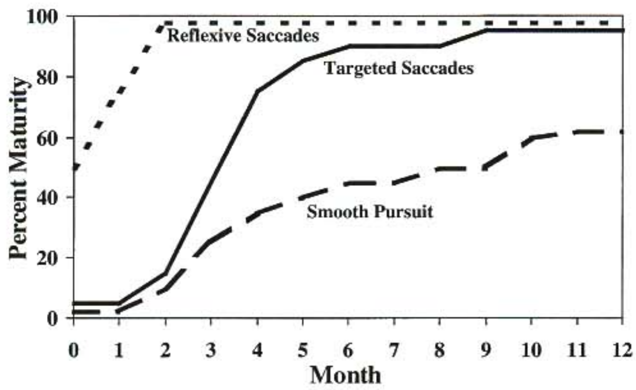

FIGURE 22.6 Development of three visual systems involved in visual tracking. The percent maturity shown as a function of months, from birth through 12 months. There are three lines, corresponding to the reflexive saccadic eye movements (Reflexive Saccades), voluntary saccadic eye movements (Targeted Saccades), and smooth pursuit eye movements (Smooth Pursuit). (From Richards and Hunter, 1998.)

There were several results from that study. As expected, there was an increase in tracking ability over this age range, smooth pursuit eye movements improved, and the infants' use of saccades to track the stimuli complemented their use of smooth pursuit eye movements. Two findings in that study are most relevant to the present chapter. As expected from the Johnson model and the age changes in the three eye movement systems described by that model, there were developmental changes in the voluntary saccadic and smooth pursuit eye movement systems but not in the reflexive saccadic eye movements. Figure 22.7 shows the smooth pursuit and saccadic eye movement results under conditions of attention and inattention. In figure 22.7, the youngest two ages (8 and 14 weeks) and the oldest two ages (20 and 26 weeks) were combined (although these results actually were graded over all four ages). The lower right part of figure 22.7 shows the saccade frequency occurring during the inattentive periods. These would be most similar to the reflexive saccadic eye movements. The younger and older infants show approximately equal numbers of these eye movements. Alternatively, in the upper panels it can be seen that saccade frequency and smooth pursuit gain showed a difference in the youngest and oldest infants. These two systems correspond to voluntary saccadic and smooth pursuit eye movements. These findings show the expected age changes for these three eye movement systems as might be predicted from figure 22.6.

A second finding from that study is also related to our current concerns. The tracking stimulus was presented at speeds ranging from "very slow" to "very fast" for the capabilities of infants' smooth pursuit (Richards and Holley, 1999). The reflexive saccadic eye movements were unresponsive to the stimulus speed (figure 22.7, lower right panel), whereas smooth pursuit tracking and saccadic tracking during attention were responsive to stimulus speed (figure 22.7, upper panels). Additionally, at the two older ages it took faster speeds before there was a significant drop in tracking gain. The complementary nature of the smooth pursuit and saccadic eye movement systems also was shown during attention. When the older infants (4.5 and 6 months of age) were attentive to the stimulus display, the infants shifted from smooth pursuit tracking to saccadic tracking as the speed of the tracking stimulus became too fast for smooth pursuit eye movements to follow (figure 22.7, cf. left and right panels). Thus during aroused attentive states the oldest infants used the smooth pursuit and voluntary saccadic eye movements to track the visual stimulus and adjusted the parameters of the eye movements according to the speed of the tracking stimulus.

The results from this study suggest at least two roles that sustained attention may play in behavior. First, the arousal system of the brain acts to energize specific brain systems involved in cognitive activities. In this study the general level of increased performance during sustained attention reflects this arousal. The simultaneous development of the eye movement systems (smooth pursuit, voluntary saccadic) and arousal system (sustained attention) resulted in a synchrony between attention and eye movement control. Second, sustained attention does more than just energize involved systems. Tracking behavior during sustained attention was preserved over increases in tracking speeds by shifting from smooth pursuit tracking to saccadic tracking when smooth tracking failed. The attention-arousal system also acts to select the appropriate behavior, given the feedback being received from the stimulus display and whatever goals the infant has in the situation.

Recognition of briefly presented visual stimuli

This section reviews studies showing the effect of sustained attention on infant recognition memory. Infant recognition memory is often studied with the paired-comparison procedure (Fagan, 1974). In this procedure infants are familiarized with a single stimulus (*familiar stimulus*) during a familiarization phase. Then, during the recognition memory test phase the familiar stimulus is paired with a stimulus not previous seen (*novel stimulus*). Recognition memory for the familiar stimulus is inferred if the infants show a novelty pref-

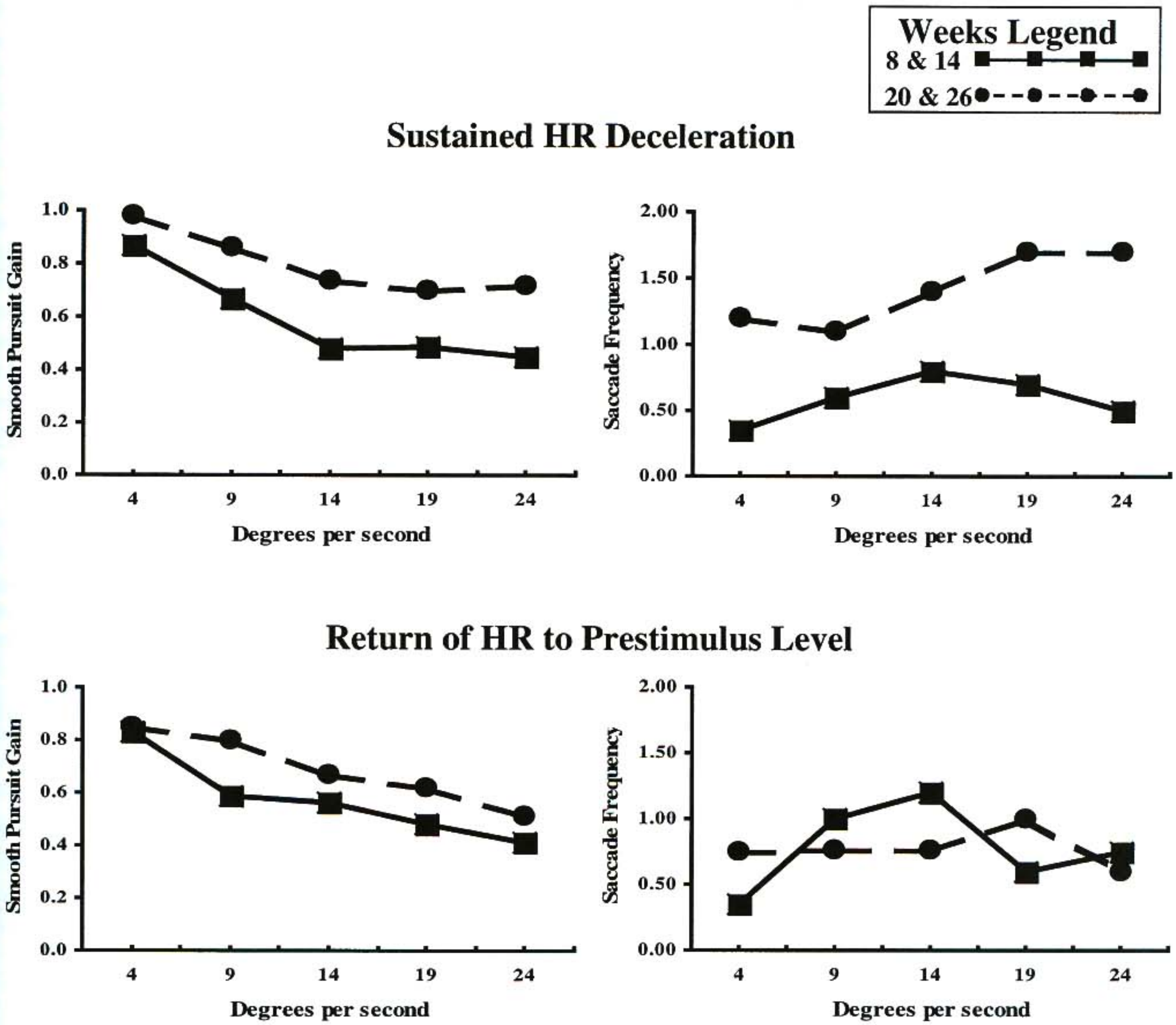

FIGURE 22.7 The smooth pursuit EOG gain and saccade frequency (saccades per second) as a function of stimulus tracking speed and testing age (8 and 14 weeks combined, 20 and 26 weeks combined). The top two plots were taken from the period when sustained heart rate deceleration was occurring, and the bottom two plots were taken from the period after heart rate had returned to its prestimulus level. (Adapted from Richards and Holley, 1999; Richards and Hunter, 1998.)

erence, i.e., look longer at the novel stimulus than the familiar stimulus during the paired-comparison test phase.

Two studies using heart-rate–defined attention phases have shown that exposure to the familiar stimulus during sustained attention results in recognition memory for stimuli presented for just 5 or 6 seconds (Frick and Richards, 2001; Richards, 1997b). In these studies infants at 14, 20, or 26 weeks of age were presented with a Sesame Street movie, "Follow That Bird," on a television monitor. This movie is very interesting to young infants and reliably elicits the full range of heart rate changes that are related to the attention phases. On separate trials, at a delay defined by the deceleration of heart rate, a delay defined by the return of heart rate to its prestimulus level, or time-defined delays, a familiarization stimulus was presented for 5 or 6 seconds. One condition with the Sesame Street movie alone was provided (no familiarization stimulus, i.e., no-exposure control) and one condition with a 20-second exposure to the familiar stimulus was presented. Following each familiar stimulus presentation, a paired-comparison recogniton memory test was done. The infants' duration of fixation on the novel and the familiar stimulus during the first 10 seconds of the test phase were recorded.

Several results showed that the infants recognized the familiar stimulus and preferred to look at the novel stimulus in the test phase, with only 5 seconds of familiar stimulus exposure. For example, when compared to the no-exposure control trial, infants looked longer at the novel stimulus than at the familiar stimulus. Furthermore, infants looked at the novel stimulus in the test phase for the brief exposure trials (5 or 6 s) as long as they did during the traditional 20-second accumulated fixation exposure trial.

The most interesting result from these studies is illustrated in figure 22.8 (Richards, 1997b). This figure shows the duration of the exposure to the familiar stimulus during the familiarization phase, but for different lengths of exposure during the sustained heart rate deceleration. That is, for some trials the infants' sustained attention overlapped the familiar stimulus exposure for only a brief period of time (e.g., <1 s), and on other trials the overlap was much greater (e.g., >5 s). This exposure is shown for different trials, and the percent fixation on the novel stimulus in the recognition memory test phase is plotted. A very brief overlap of sustained attention and the familiar stimulus resulted in novelty preference scores at or below the no-exposure control condition. As the amount of familiar stimulus exposure during sustained attention increased, there was a corresponding increase in the novelty preference. This positive correlation between familiar exposure during sustained attention and later recognition memory level (novelty preference level) implies that incorporation of stimulus information is accomplished when the infant is in a highly aroused (attentive) state.

We also have shown that the distributions of the fixations on the novel and familiar stimulus in the test phase of the paired-comparison recognition memory procedure are affected by the infants' attention state (Richards and Casey, 1990). In that study heart rate was recorded and the heart-rate–defined attention phases were evaluated during the test phase of the recognition memory procedure. The infants showed novelty preference, indicating recognition memory, primarily during sustained attention. For example, on the average in these 3–6-month-old infants, there was about 11.8 s of sustained attention on the recognition memory test phase. Of this, about 7.3 s was spent looking at the novel stimulus and 4.5 s was spent looking at the familiar stimulus. Alternatively, during attention termination (or inattentiveness) the infants spent equal amounts of time looking at the novel and familiar stimulus. And on no-familiar-stimulus trials (no-exposure control) there were equal amounts of looking at the novel and familiar

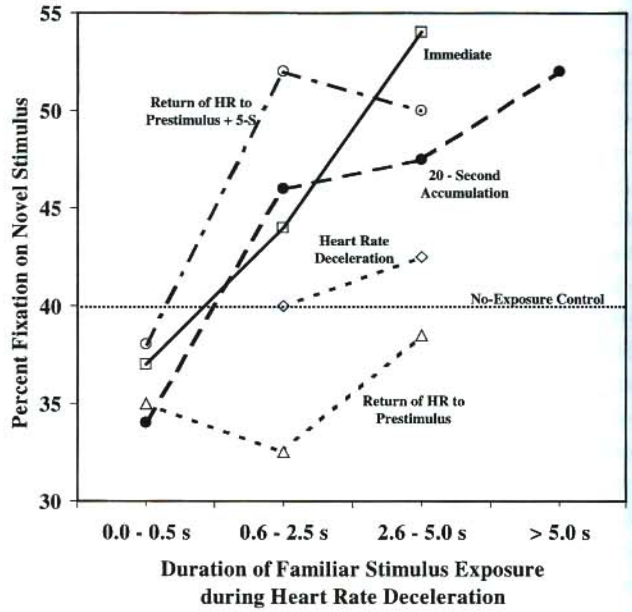

FIGURE 22.8 The duration of familiar exposure occurring during heart rate deceleration (sustained attention) and the percent fixation on the novel stimulus in the recognition memory test phase. The no-exposure control time (40%) should be considered the baseline percent fixation with no exposure to the familiar stimulus. (Adapted from Richards, 1997.)

stimulus during each phase. These results show that the exhibition of recognition memory generally takes place during sustained attention, when heart rate is below baseline. That is, the infants recognize the familiar stimulus and move fixation to the novel stimulus. This move to the novel stimulus most likely is to acquire new stimulus information. Thus the exhibition of recognition memory during this paired-comparison procedure, shown as novelty preference, is precisely the infant's attempt to acquire new information from the previously unseen stimulus during sustained attention!

We are now conducting a study to examine the effect of attention on individual cognitive processes that may occur in the brain upon exposure to familiar and novel stimuli (preliminary data presented in Richards, 2000b). Nelson and colleagues (Nelson and Collins, 1991, 1992; Nelson and deRegnier, 1992; Nelson and Salapatek, 1986; also see reviews by Nelson, 1994; Nelson and Dukette, 1998; Nelson and Monk, this volume) and others (Karrer and Ackles, 1987, 1988; Karrer and Monti, 1997; Courchesne, 1977, 1978; Courchesne, Ganz, and Norcia, 1981) have examined infant recognition memory recording ERPs during stimulus presentations of very brief duration (~150 ms). These studies use the "oddball" paradigm in which one stimulus is presented relatively frequently and a second stimulus is presented infrequently. These studies report 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 Nc (negative central) component (Courchesne, 1977, 1978). In most studies the Nc component is larger to the infrequently presented stimuli and is thought to represent a general attentive state or alerting to the presence of a novel stimulus. If the frequently presented and infrequently presented stimuli are already familiar to the infant, the Nc component does not differ (Nelson and Collins, 1991, 1992). This distinction does not occur in 4-month-old infants (Karrer and Ackles, 1987; Nelson and Collins, 1991, 1992) but does occur in infants 6 months old and older.

These oddball procedure studies also report later components in the ERP. These components are slowly changing positive or negative potential shifts from about 800 to 1500 ms following stimulus presentation. Nelson and Collins (1991) reported that in 6-month-old infants there are three distinctions that may be made. First, a familiar stimulus that was presented infrequently (infrequent familiar, IF) resulted in an increased slow-wave positivity in this later period relative to the ERP observed when the familiar stimulus was presented frequently (frequent familiar, FF). Second, a series of stimuli that were never previously presented to the infant and were presented infrequently (infrequent novel, IN) were presented. These stimuli resulted in a negative slow wave component in this later interval. Thus, these novel stimuli show that infants were sensitive to novelty per se (IN versus IF) as well as the relative probability of stimulus occurrence (IF versus FF). As with the Nc component, at 4 months of age there was no difference between the later occurring slow waves, whereas by 6 months of age (Nelson and Collins, 1991) or 8 or 12 months (Nelson and Collins, 1992; Nelson and deRegnier, 1992) these three stimulus presentation procedures resulted in differing ERP potential shifts.

We are currently conducting a study using this procedure, measuring ERPs, and presenting the FF, IF, and IN stimuli in different phases of attention (Richards, 2000b). As with the other studies of infant recognition memory (Frick and Richards, 2001; Richards, 1997b) the infant's attention is elicited with a Sesame Street movie, "Follow That Bird," that elicits the heart-rate–defined attention phases. Then, during stimulus orienting, sustained attention, or attention termination, the brief visual stimuli are presented overlaying (replacing) the attention-eliciting stimulus. These briefly presented stimuli consist of static computer-generated patterns that are easily discriminable by infants at these ages (e.g., checkerboard pattern, circles, squares). We have data from 6-month-old infants and are currently testing 4.5- and 7.5-month-old infants to extend these findings to other ages and to test developmental changes occurring in these memory processes.

Figure 22.9 shows ERP changes from the central (Cz) and parietal (Pz) leads in 6-month-old infants in response to the visual stimuli. The top two graphs show the ERP changes for the first stimulus on each trial (stimulus orienting), during sustained attention, and during inattentiveness. The ERP changes in these two graphs show a significantly larger Nc component (negative component about 400–700 ms) for the "attentive" phases (stimulus orienting, sustained attention, dashed lines) compared to the "inattentive" phase (attention termination, solid line). This confirms the idea that the Nc component represents an "attention-alerting" mechanism that occurs in response to any visual stimulus. The bottom two graphs of figure 22.9 show the ERP changes for the three presentation procedures (FF, IF, and IN) only for the presentations occurring during sustained attention. The Nc is not different for these three procedures, but the slow wave portion of the graphs (750–1500 ms) shows a large positive slow wave for the infrequent familiar presentation and a smaller negative slow wave for the infrequent novel stimulus. The stimulus presentations occurring during inattention did not show the slow wave differences between the three presentation procedures (not shown in figure 22.9).

Figure 22.10 (see color plate 15) shows topographical maps of the Nc and a later slow wave for the IF and FF stimuli during sustained attention. These show the Nc component as a widespread negativity in the central area of the scalp occurring for the frequent and infrequent familiar stimuli, but the later slow wave component occurred primarily in the frontal-central regions only for the infrequently presented stimuli.

The relation between sustained attention and infants' recognition of briefly presented visual stimuli shows that the arousal form of attention is related to complex infant cognition. Recognition memory is accomplished by several brain areas and cognitive functions. It requires the acquisition of stimulus information and memory storage over some period of time. The measurement of recognition memory also requires performance on a task exhibiting the existence of the stored memory. The results of these studies show that the arousal aspect of attention may "invigorate" each of these cognitive processes. This enhances familiarization when information acquisition is occurring, may facilitate memory consolidation during the waiting period, and enhances the processes involved in the exhibition

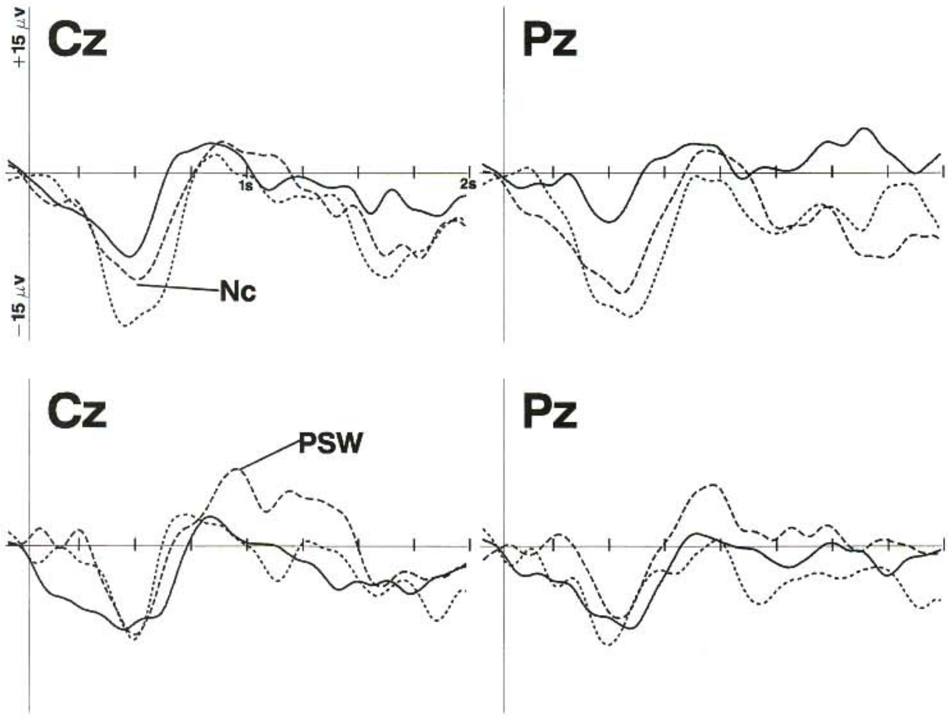

FIGURE 22.9 The ERP in response to the frequent familiar, infrequent familiar, and infrequent novel presentations for 6-month-old infants. These recordings are from the Pz (parietal scalp area) and Cz (central scalp area) leads. The top two plots represent the ERP for the first stimulus in a trial (stimulus orienting, small dashes), when sustained heart rate deceleration was occurring (sustained attention, long dashes), and when heart rate had returned to its prestimulus level (attention termination, solid line). The Nc component is identified on the Cz recording. The bottom two plots represent the ERP occurring during sustained attention for the frequent familiar (solid line), infrequent familiar (long dashes), and infrequent novel (short dashes) presentations. The positive slow wave (PSW) is identified for the ERP to the infrequent familiar stimulus.

of recognition memory. The effect on recognition memory is true for the overall responses to the stimulus in the paired-comparison recognition-memory test phase (Richards and Casey, 1990) and for the individual cognitive processes occurring for transient responses to the stimulus (Richards, 2000b).

Conclusions

Attention shows dramatic development in the early period of infancy, from birth to 12 months. This chapter has emphasized an attention system that represents a general arousal of cognitive functions. The system in the brain controlling this arousal develops in the first few months of life, and this brain development is responsible for the behavioral/attentional development seen in young infants. This chapter reviewed several studies that showed the effect of this arousal system, indexed by heart rate changes showing sustained attention. There were developmental changes in infant sustained attention that were reflected in developmental changes in specific attentional systems or that corresponded to developments occurring in other brain-based attention-directed infant behavior.

There are three ways in which future research and progress in the study of the development of attention-arousal in infants could progress. First, this review was limited to studies using heart rate as a measure of the general arousal system in the brain. There are other measures that may be useful in this regard. For example, continuous levels of EEG activity are thought to be influenced by general arousal mechanisms in the brain. Since the EEG represents the summed activity of large groups of neurons, one might expect that the brain areas controlling arousal or the neurochemical systems should have an influence on overall neural activity (extent, duration, and localization). Thus, measures of EEG such as spectral power and coherence may give information about arousal. Such measures also may show relatively localized CNS arousal.

A second area in which research on the development of the brain systems controlling arousal may benefit is

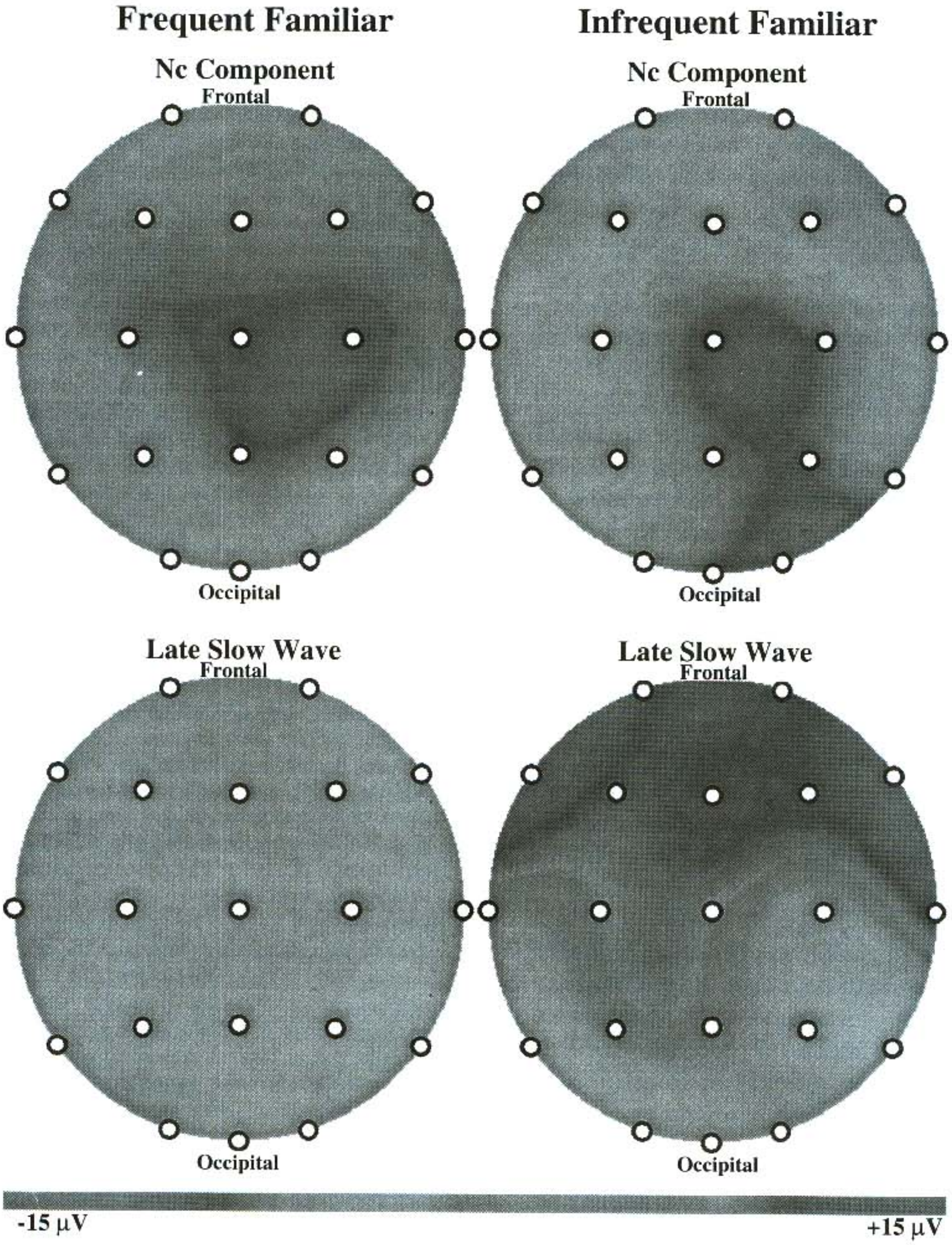

FIGURE 22.10 A topographical mapping of the ERP components occurring during sustained attention. The ERP components were the Nc (400–700 ms; top figures) and the later slow wave component (700–1500 ms; bottom figures) taken during the presentation of the frequent familiar (left figures) and the infrequent familiar (right figures) stimuli. The data in each figure represent an 80-ms average of the ERP for the Nc (centered at 560 ms) and the slow wave (centered at 1120 ms) components for the 20 recording electrodes. The data are plotted with a cubic spline interpolation algorithm, with an averaged electrode reference, and represents absolute amplitude of the ERP for the recorded data rather than difference ERPs.

direct measures of the brain. Such measures in animal models have included invasive chemical manipulations and measurement as well as destruction of the areas controlling arousal through lesions or neurochemical inhibitors. These measures cannot be applied in infant participants because of ethical considerations. However, noninvasive measurements from psychophysiological measures that are tuned to specific neurochemical systems might be found. Perhaps one type of quantitative activity in the EEG may be linked to a specific neurochemical system and another type linked to another system. The simple recording of EEG, ERP, or heart rate cannot be used to distinguish the four arousal systems detailed in Robbins and Everitt (1995). The EEG and heart rate would be expected to respond to any manipulation of an underlying arousal system. Some type of quantitative activity in the EEG would have to be linked to the underlying neurochemical system in order to use psychophysiological measures for this direct evaluation of the brain systems controlling this arousal form of attention.

Finally, the measurement of brain function for specific attentional systems may have the brightest future for studies of infant attention. Techniques such as high-density EEG and ERP recording should lead to the identification of specific cortical areas involved in attention in infants. High-density ERP recording allows the use of cortical localization techniques in which the locations on the cortex thought to generate the ERP activity are identified. The increased resolution of 64 or 128 electrodes allows the localization of such sources with increased accuracy relative to the 19 electrodes used in the traditional 10–20 recording montage. Johnson and colleagues (Csibra, Tucker, and Johnson, 1998, 2001; Johnson, Gilmore, and Csibra, 1998; also see Johnson, Mareschal, and Csibra, volume) and I (Richards, 2000c, 2001) have been using such high-density EEG recording techniques in the study of attention-linked saccadic eye movements. These techniques could be expanded to study several brain areas involved in infant attention. This work is still in its infancy, but the use of these techniques should be profitably applied to an understanding of the developmental changes in brain areas that are involved in the development of infant attention. Such techniques will lead to a more informed developmental cognitive neuroscience approach to the development of attention in young infants.

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