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Infant Attention, Arousal, and the Brain

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Leslie B. Cohen is a pioneer in many areas of infant cognitive development. One line of research "founded" by his early work is the examination of multiple attention types in infants, employing behavioral and experimental manipulations (e.g., Cohen, 1972). This work led to the study of several types of attention in young infants and is now paying off in the identification of brain areas involved in infant attention. Developmental psychologists are beginning to understand how neural activity underlying infant cognitive processes is facilitated by attention.

The current chapter is a summary of a line of research that I have been following for more than 25 years on the topic of "multiple attention types." This work has been inspired by the information-processing tradition that asserts that attention is one way that information is selected for evaluation from a broad range of available stimulation. This approach was studied behaviorally first by Cohen (e.g., 1972), but has expanded to affect nearly all of infant cognitive developmental work. I will emphasize the aspects of my own work that have examined the information processing aspects of infant attention, and the neural basis of attention. This is a selective review that traces some "prescient" conclusions drawn by Cohen regarding the nature of differing attention types, but also expands upon those views to examine the neural basis of attention. The review is selective, in that it neither fully reviews the field of infant attention, nor is it a full review of my work in this area.

TWO PHASES OF INFANT ATTENTION (WITHIN A LOOK)

> "Whatever conclusions are reached from the studies, the present investigation has already demonstrated the feasibility, perhaps even the necessity, of independently assessing attention-getting and attention-holding aspects of infant visual fixations." L. B. Cohen, (1972, p. 878)

The start of the behavioral work on infant attention types is easily traced to a single study of Cohen's in 1972 (Cohen, 1972). An important

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methodological advance in this study was the "infant-control" presentation procedure. The visual patterns were presented, and online evaluation of the direction of infant fixation was made. As long as the infant looked toward the visual pattern, the pattern remained on. When the infant looked away from the pattern, it was turned off. The duration of fixation toward the pattern was both the dependent variable and the variable controlling stimulus duration. The infant control procedure differed from previous presentation methods in which the stimulus was presented for a fixed period of time, the infant looked toward the stimulus and away from it several times, and the dependent variable was the amount of looking time over the entire duration of the fixed stimulus interval (Brennan, Ames, & Moore, 1966; Kagan & Lewis, 1965). Cohen (1972) argued that the infant control procedure was preferable because it did not confound patterns of looking (and looking away) with the infant's transitory fixations, and thus offered an improved measure of attention. Duration of fixation toward the stimulus was the measure of "visual attention." Incidentally, for similar reasons, the infant control procedure apparently was "discovered" independently by Horowitz, Paden, Bhana, and Self (1972).

One of the reasons Cohen gave for preferring the infant control procedure was that it was the most relevant to the distinction of attention types. The total fixation duration on a fixed-duration presentation procedure could come from a number of brief looks, or a single long look. Presupposing that the beginning of fixation is affected by one process, and the total duration of fixation is determined by other processes, the same amount of accumulated fixation for the multiple looks and the single looks would obscure the underlying attention processes. The length of a single look toward the stimulus in the infant control procedure would be a better measure of the processes holding fixation toward the stimulus. The process controlling behavior at the beginning of the look was labeled "attention-getting," and the process keeping fixation toward the stimulus was labeled "attention-holding."

How were attention-getting and attention-holding examined in this study? Infants at four months of age were presented with visual patterns that consisted of black and white checkerboards. The checkerboard patterns were of varying size and number. Earlier work had hypothesized that there was a relation between infant age and the complexity of visual stimuli that elicited attention. Thus, it was expected that infants should show varying amounts of attention to the patterns. The stimulus was presented when the infant was looking toward a blinking light that was located away from the presentation screen. Cohen measured the latency of the look from "off-screen" to "screen" following the onset of the checkerboard stimulus on the screen. The infant control procedure was used to determine the duration of the stimulus presentation, and this also was the duration of "visual attention." The most important finding from this study was that different aspects of the stimuli affected look latency and look duration. The size of the squares in the checkerboard was most important in influencing the latency to look toward the checkerboard screen, whereas the number of squares in the checkerboard was most

influential in the duration of looking. Cohen concluded from this finding that this method could be used to measure the attention processes at the beginning of fixation (attention-getting) and attention processes occurring during fixation (attention-holding).

Cohen's study made two very important contributions. First, the infant control procedure was introduced, and provided a new method for studying infant visual attention. I will come back to the importance of this in the next section. Second, Cohen's proposal was that attention was not a unitary process. Rather, there are different types of underlying processes that affect attention. The "getting" and "holding" further implies that differing types of attention are being studied sequentially. Attention first begins (attention-getting), followed by attention being sustained by the stimulus (attention-holding). The sequential nature of these attention "types" leads to the notion that attention goes through "phases" during visual fixation. The methodological advance (infant control procedure) made it possible to identify the theoretically distinct attention phases.

MULTIPLE ATTENTION PHASES DEFINED WITH HEART RATE

> "Taken together, the two studies support Cohen's hypothesis that infant attention involves at least two different mechanisms: an attention-getting process which determines whether or not the infant will orient toward a stimulus projected in his periphery, and an attention-holding process determining how long his gaze will be maintained once he fixates."
> L. B. Cohen (1972, p. 877).

One of the conclusions from the Cohen (1972) study was that there were "at least two" different mechanisms in infant attention, the attention-getting and attention-holding mechanisms. The previous section reviewed the importance of the methods and the theoretical conclusions reached by Cohen on the basis of this work. However, around the same time, psychologists interested in infant cognitive development were using heart rate as a measure of attention (e.g., Graham, 1970, 1979, 1992; Graham, Anthony, & Zeigler, 1983; Porges, 1976, 1980). They concluded that there may be several components of attention that occur in a "stimulus-processing event." I will review some of this work, and present a model for using heart rate to index multiple phases of attention within an infant's look in the infant control procedure. I have reviewed this work in several places (Berg & Richards, 1997; Reynolds & Richards, 2007; Richards & Casey, 1992).

Sokolov (1963) had asserted that physiological measures could be useful in distinguishing the human response to environmental stimuli. Well-known processes relevant to attention research first studied by Sokolov in adult participants were the orienting response, habituation, and sensitization. Graham and Clifton (1966; nee Rachel Keen) proposed that heart rate could be used to distinguish orienting process (heart rate deceleration) from other activation responses such as defensive responses (heart rate acceleration;

may be plotted across time in the same time resolution as the ERP (Figure 2.6, far right). This temporal activity is presumed to represent the temporal extent of the neural activity for the brain area(s) generating the Nc ERP component. The representation of the dipoles inside the head, and the projection of the electrical currents on the scalp, is the "spatial" aspect of this work, and the neural activity unfolding in time is the "temporal" aspect. So far, we have "spatiotemporal infant neuroimaging" of the Nc ERP component.

The most important aspect of this work to cognitive development is the functional relation of the putative neural activity to experimental events or cognitive processes. Recall that the Nc is hypothesized to represent the orienting of attention based on a primitive recogniton of the novel stimuli vis-à-vis the familiar stimuli. We can examine the activity of the cortical sources in relation to the experimental events. Figure 2.7 (top figure) shows the activity of the dipoles located in the inferior prefrontal cortex as a function of time and the three stimulus testing conditions. The activity shows a large deflection in the negative direction at about 500 ms. This represents enhanced neural

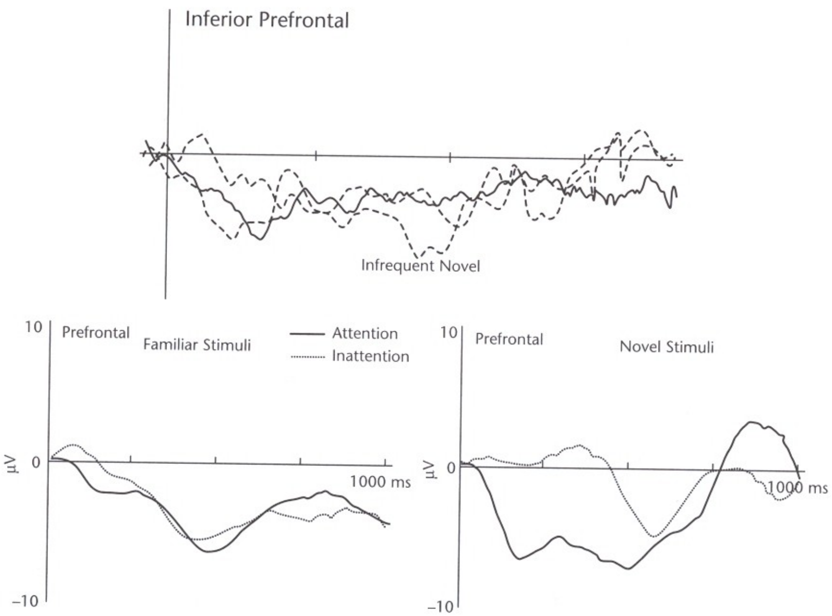

Figure 2.7. The temporal activity of the cortical current sources for the inferior prefrontal brain areas, as a function of the brief stimulus presentation procedures (top figure); effect of brief stimulus familiarity (left bottom figure, familiar stimuli; right bottom figure, novel stimuli) and attention (solid line, attentive; dashed line, inattentive) on the temporal activity of the current sources located in the prefrontal cortex. *Source*: Adapted from "Familiarization, attention, and recognition memory in infancy: An ERP and cortical source localization study, " by G. D. Reynolds and J. E. Richards, 2005, *Developmental Psychology, 41*, p. 608. Copyright 2005 by American Psychological Association.

activity in this area, projected on the scalp as a negative electrical potential. This activity is larger for the novel stimulus than for the two familiar stimuli. We believe that this represents one of the areas of the brain that generates the Nc. The relation to the stimulus conditions affirms the functional significance of the cortical sources in this area of the brain. The activity of the cortical sources can also be related to cognitive processes. Figure 2.7 (bottom figures) show the summed activity from dipoles located in the inferior prefrontal cortex, anterior cingulate, and posterior-superior prefrontal cortex, as a function of stimulus familiarity and attentiveness (Reynolds & Richards, 2005). The figure on the lower left shows that the ERP response to the familiar stimuli was not affected by attention status. On the other hand, when the infant was attending, there was a large increase in the activity of the cortical dipoles nearly immediately upon stimulus presentation that lasted for several hundred ms (Figure 2.7, bottom left, solid line). This increased activity represents the enhanced and efficient processing occurring in this cortical area when the arousal system is activity. We have a "spatiotemporal functional neuroimaging" technique to investigate infant attention!

SUMMARY AND FUTURE DIRECTIONS

This chapter reviewed work being done on infant attention that was inspired by the early work of Cohen (e.g., Cohen, 1972). Several aspects of this work were directly influenced by a conception of the sequential unfolding of multiple attention phases, first explicitly summarized by Cohen. Some recent work has been to examine some "stimulus" variables that affect infant attention development, including the role of attention in controlling extended visual fixations in television program viewing (Courage, Reynolds, & Richards, 2006; Hunter & Richards, submitted; Richards & Anderson, 2004; Richards & Cronise, 2000; Richards & Gibson, 1997; Richards & Turner, 2007). This work continues to find aspects of infant attention both consistent with Cohen's early views on attention, and aspects of attention that were unanticipated in 1972.

The second aspect of my work that has been reviewed in this chapter is the development of neurodevelopmental models of infant attention. I reviewed an explanatory neural model for the heart-rate-defined attention phases, as well as some work that looks "inside the baby's head" to find how the brain arousal system, measured by heart rate changes, affects neural processes involved in cognition and attention. Developmental changes in the brain can now be related to developmental changes in attention, perception, cognition, and behavior with the "spatiotemporal functional neuroimaging" techniques I am developing.

This neuroimaging work requires further advances. Grey Reynolds and I describe in some detail an application of cortical source analysis of ERP to infant participants (Reynolds & Richards, 2009). We note in that chapter that the MRI recording done with infant participants will go a long way to eliminating some deficits of this approach. Specifically, there are topological characteristics of the infant's brain inside the skull that differ dramatically

Graham & Clifton, 1966). Graham in several places developed this work further (Graham, 1970, 1979, 1992; Graham et al., 1983). She claimed that heart-rate responses to a sudden-onset, moderate-intensity stimulus, first produced an automatic interrupt that was a transient detection of the stimulus change. This was indicated by a brief change in heart rate. Then, if the infant continued being interested in the stimulus, a longer-lasting stimulus orienting would occur, indicted in heart rate by a large deceleration. Graham and several colleagues showed that infants' responses to auditory and visual stimuli showed this pattern of response (Graham, 1970). Much of Graham's work examined the responses to relatively brief stimuli, presented for a fixed duration (e.g., the fixed duration stimulus presentation). Porges (1976, 1980) began using heart rate in response to much longer sustained stimuli. He suggested that another, more sustained attention response occurred after stimulus orienting. The work of Graham and Porges implied that heart rate might index a sequence of qualitatively different aspects of attention in response to the presentation of visual stimuli.

The similarity of this work to Cohen's distinction between attention-getting and attention-holding is obvious. The short-latency, transient-detection reaction, indexed by a brief heart rate change, interrupts the ongoing cognitive processes and attracts processing to a new stimulus. This redirects attention toward the new stimulus—"attention-getting." The stimulus orienting that occurs are the initial stages of information processing, and the sustained stimulus processing to sustained stimuli—reflected in heart rate deceleration and continued heart rate change—reflect the active attention to the stimulus. This continued stimulus processing is similar to Cohen's "attention-holding" phase.

I was perhaps the first to use heart rate together with the infant control procedure, with the specific goal to study the more extended aspects of stimulus processing (Richards, 1987). In my studies infants were presented with a range of stimuli, including simple visual stimuli, geometric patterns, visual stimuli linked with auditory stimuli, and complex multidimensional dynamic stimuli. There is a ubiquitous pattern of heart rate change that occurs in the infant control procedure. Figure 2.1 shows the heart rate change in infants ranging in age from 3 to 6 months when presented with simple geometric patterns in the infant control presentation method (Richards & Casey, 1991). There is a large deceleration of heart rate that occurs at the beginning of the look toward the stimulus (or stimulus onset, if the infant is already looking). This is followed by a sustained lowered heart rate for some period of time, after which heart rate returns to its prestimulus level. This all occurs within the look toward the stimulus controlled by the infant's fixation. At some point the infant looks away from the stimulus.

I have proposed a model that hypothesizes multiple phases of attention occurring sequentially during the course of a single look toward the stimulus (Reynolds & Richards, 2007; Richards & Casey, 1992). The "pre-attentive" phase consists of the automatic transient-detection system which directs attention towards the stimulus. Stimulus orienting then occurs, lasting for 4 to 5 seconds, and indicated by the rapid deceleration of heart rate. Stimulus orienting is

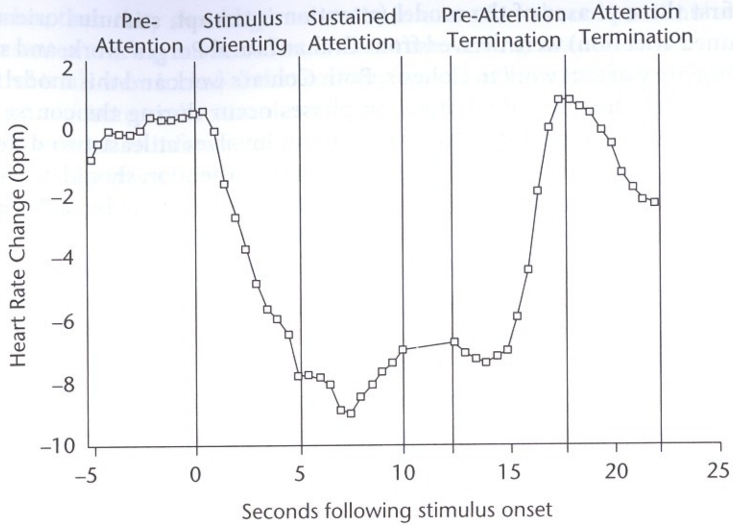

Figure 2.1. The heart-rate-defined phases of attention in 3- to 6-month-old infants. *Source*: From "Heart rate variability during attention phases in young infants," by J. E. Richards and B. J. Casey, 1991, *Psychophysiology, 28*, p. 46. Copyright 1991 by Wiley-Blackwell. Reprinted with permission.

characterized by an initial registration of the physical properties of the stimulus, but only limited information processing occurs during this phase. Following stimulus orienting, given that the stimulus is interesting to the infant, sustained attention begins. Sustained attention is indicated by a prolonged lowered heart rate. The duration of sustained attention is variable, affected by the infant's age, the complexity of the stimulus, the relation between the background context and the stimulus, and other variables. Sustained attention represents the period of time in which information and stimulus processing occurs. Attention termination is a final phase of attention occurring in the infant control procedure, within a look toward the visual stimulus. This phase is preceded (marked by?) a return of heart rate to its prestimulus level. Immediately after heart rate returns to its prestimulus level, the infant is less responsive to external stimulation than during the other phases. This phase may be followed by continued fixation on the stimulus, with heart rate remaining at the same level as it was during the prestimulus period, indicating a period without active attention engagement—or, the infant is very likely to look away from the stimulus during attention termination, or this inattentive period. Note that the use of the entire duration of fixation in the infant control procedure, as the measure of infant visual attention ("attention-holding" phase), is unlikely to be correct. The model I have proposed suggests that there can be significant periods of time in which stimulus information processing does not occur, or which vary on the amount of information processing that does occur.

This model of sequential heart-rate-defined attention phases has many similarities to the conclusions reached by Cohen from his behavioral study.

The first three phases of the model (attention-interrupt, stimulus orienting, sustained attention) were derived from Graham's and Porges' work, and share the similarity of that work to Cohen's. Both Cohen's work and this model support the idea that sequential attention phases occur during the course of a look. Cohen's statement that "infant attention involves at least two different mechanisms" was prescient in its recognition that attention should be parsed into multiple phases. However, the "at least" has turned out to be "at least five phases of attention."

INFANT "ATTENTION-HOLDING" INVOLVES INFORMATION PROCESSING

> "On the other hand, Cohen (1969) has provided some evidence for the hypothesis that attention holding involves more active information processing and may be influenced more by the variability, amount of edge, or novelty of the pattern." L. B. Cohen (1972, p. 878)
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> "Everyone knows what attention is. It is the taking possession by the mind, in clear and vivid form, on one out of what seem several possible objects or trains of thought.... The immediate effects of attention are to make us: a) perceive b) conceive c) distinguish d) shorten 'reaction time'—better than otherwise we could..." William James, *Principles of Psychology*, 1890

Cohen (1972) concluded that the attention-holding mechanism involved more information processing, and was more influenced by a variety of experimental factors, than was the attention-getting process. Cohen's conclusion is consistent with William James' assertion that attention has the effect of enhancing psychological processes, and he attributed this aspect of attention to the attention-holding aspect of infant attention. In the current section I will present a study demonstrating that information processing occurs primarily during the period of "sustained attention," defined by heart rate changes (Reynolds & Richards, 2007; Richards & Casey, 1992).

I will review one study that showed the effect of information processing occurring during sustained attention on a subsequent measure of recognition memory (Frick & Richards, 2001; Richards, 1997). Infants were first presented with a Sesame Street movie, "Follow that Bird," on a television monitor. This movie elicits the heart rate changes associated with attention, including sustained attention, attention termination, and periods of inattentiveness. The heart rate changes were monitored in real time by digitizing the ECG, identifying the R-wave in the ECG, calculating interbeat intervals, and determining when a significant deceleration occurred in heart rate (sustained attention) or when heart rate returned to its prestimulus level after the deceleration (attention termination). Then—at points defined by time, the occurrence of sustained attention, or the occurrence of attention termination—a simple black and white geometric pattern replaced the movie for 2.5 or 5.0s, and then the movie was continued for several seconds. If sustained attention represents the period of time that infants are processing the information in the visual

stimulus, then they should garner more information about the stimulus if it is presented during sustained attention than during attention termination. Control trials were included that contained no-familiarization stimulus exposure, or exposure to the stimulus for 20s.

The amount of information processing was estimated with a paired-comparison recognition memory procedure (Fagan, 1974). This procedure tests recognition memory by presenting the infant with familiar and novel stimuli. Recognition memory is inferred if the infant looks longer toward the novel stimulus than the familiar stimulus, i.e., "novelty preference." Figure 2.2 illustrates the results from this study, with the x-axis showing the duration of exposure to the familiarized stimulus during sustained attention, and the y-axis showing the novelty preference). The most obvious result in this figure is the positive linear correlation between the amount of sustained attention exposure and the resulting novelty preference measure. This was true in the trials when the stimulus was presented immediately, for the 20-s procedure, for the heart rate deceleration procedures, and when the presentation occurred 5s after attention termination occurred.

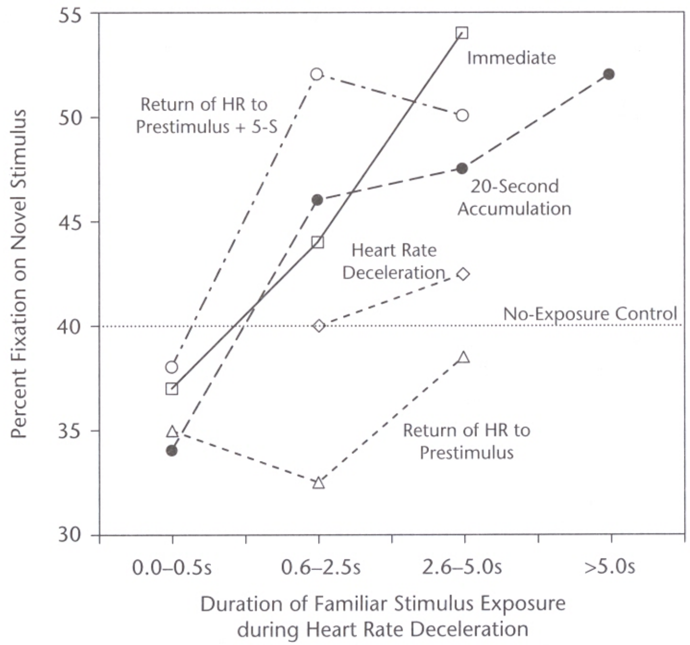

Figure 2.2. Novelty preference (recognition memory) as a function of familiar stimulus exposure during heart rate deceleration (sustained attention) for 3- to 6-month-old infants.
Source: From "Effects of attention on infants' preference for briefly exposed visual stimuli in the paired-comparison recognition-memory paradigm," by J. E. Richards, 1997, *Developmental Psychology*, *33*, pp. 28. Copyright 1997 by American Psychological Association.

There are two general points to be made from this figure. First, the positive relation between sustained attention and novelty preference occurred even when the infant was exposed to the stimulus for 2.5, 5, or 20s. That is, it was the quality of processing during stimulus exposure that affected the subsequent recognition, not the total quantity. Five seconds of sustained attention in the brief exposure conditions resulted in as much recognition memory as five seconds of sustained attention, in addition to 15s of non-sustained attention (20-s condition). Second, stimulus presentation during attention termination ("Return of HR to Prestimulus") actually resulted in longer fixation times toward the familiar stimulus than toward the novel stimulus. This was interpreted as evidence that the attention-termination phase was inhibiting processing of the stimulus (or, allowing only partial information processing) so that the infant actually shows a "familiarity preference." This implies that there is a separate attention phase beyond "attention-holding," where fixation is held toward the stimulus, but information processing does not occur. This study confirms Cohen's proposition that there are multiple types of attention during the course of a look toward a stimulus, that information processing occurs primarily during "attention-holding," but adds additional phases of attention beyond the attention-holding stage.

Many studies have been done that show this association between information processing and sustained attention. I have reviewed my own work on this issue in several places (Reynolds & Richards, 2007; Richards, 2007). Several of these studies have included a direct measure of information processing, such as recognition memory, and show a similar relationship between sustained attention and the amount of recognition memory. A number of studies also have shown the selective aspect of attention ("It is the taking possession by the mind, in clear and vivid form, on one out of what seem several possible objects or trains of thought."—James, 1890). This is shown, for example, in a lack of distractibility from looking at a central stimulus by a peripheral stimulus during sustained attention, and not during stimulus-orienting or attention-termination phases (e.g., Richards, 1987). I also have shown that there is a "top-down" influence of sustained attention on reflex stimulus-interrupt processing, exogenous orienting toward peripheral stimuli, and in eye-movement systems involved in saccadic- and smooth-pursuit tracking. These studies affirm Cohen's conclusion regarding the processing that occurs during "attention-holding" and the relation of the attention-holding process to several interesting psychological variables.

INFANT "ATTENTION-HOLDING" IS NONSPECIFIC AROUSAL: BRAIN BASIS

> "Back when Les and I were young (in the 1960s and 1970s), my slogan was 'The way to the head is through the heart' because I was using heart rate to indicate what was going on in the baby's head." (Keen, 2008)

How does the brain operate to control infant attention? There has been a general feeling that research on infant attention tells us something about what

is happening inside the baby's head. Many researchers interested in infant attention and its development have moved heavily toward neurodevelopmental models of attention. In this section I will review a model of the neural basis for the heart-rate-defined attention phases. In the following section I will review how these attention phases might influence other types of cortical processing.

The general body of literature on infant attention has not been concerned with the neural basis of attention. On the other hand, the psychophysiological literature concerning attention has had a neural model as its founding principle. The first work using "stimulus orienting," "orienting reflex," "habituation," and "sensitization" was done by Sokolov (e.g., Sokolov, 1963). Sokolov used a wide variety of physiological measures (heart rate, skin conductance, respiration) to measure the human response to environmental stimuli. Sokolov argued that the initial presentation of a "novel" (or not recently presented) stimulus produced a conflict between a "neural model" of the current environment and the sensory processes occurring in the brain. This conflict resulted in an "orienting reflex" that was reflected in a wide variety of physiological systems, e.g., skin conductance changes, heart rate deceleration or acceleration. The repeated presentation of the stimulus resulted in a modification of the neural model of the environment so that the neural model matched the sensory processes, leading to a decrease in the physiological system response to the stimulus. This decreasing response is the definition of habituation. Sokolov was the first "cognitive psychophysiologist" and, through his neural model and measurement of physiological activity, maybe the first "cognitive neuroscientist."

Many researchers interested in infant attention adopted the general research program begun by Sokolov, though not necessarily his emphasis on the brain control of attention. On one hand, Cohen and many workers adopted the orienting reflex and habituation processes as tools to study a wide variety of infant cognitive processes. However, they were unconcerned with the "neural model" and did not use physiological measures routinely in their work. On the other hand, there has been a continuing use of psychophysiological experiments with infant participants. This was probably generated by Graham and Clifton's (1965; nee Rachel Keen) review of the bidirectional nature of heart rate. And, there has been a continuing use of heart rate to distinguish attention types for infant participants (e.g., see reviews by Reynolds & Richards, 2007; Richards, 2007).

I have presented a model for explaining the relation between the heart-rate-defined attention phases and neural processes (Richards, 2001, 2007) and I will briefly review this here. One aspect of attention hypothesized by cognitive neuroscience is the arousal associated with energized activity (Posner, 1995). Arousal in this sense is the enhanced behavioral performance when attention is aroused, and not emotional arousal or sleep-state arousal. This arousal function is controlled by specific and distinct neural systems. In particular, the noradrenergic and cholinergic neurotransmitter systems control the arousal aspect of attention. Figure 2.3 shows the nuclei and distribution of these two neurotransmitter systems. These brain processes have large nuclei centers in the locus coeruleus and reticulated mid-brain area (noradrenergic) and basal forebrain (cholinergic). These neurons have long axonal processes that ascend and have terminal endings throughout the cortex, have a direct influence on the thalamus, and have descending connections to several midbrain systems. When these neurons are active, they release the relevant neurotransmitter in the brain areas where the terminals end. These neurotransmitters are then available for increased neural efficiency of the target areas. Thus, the brain areas receiving the neurotransmitters act more efficiently when these neurotransmitter systems are active. These two neurotransmitter systems are active in response to novel incoming sensory stimuli, as well as from top-down cortical influences. 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.

The heart-rate-defined attention phases are markers of these two arousal systems (Richards, 2001, 2007). The neural control of heart rate originates from cardioinhibitory centers in the orbitofrontal cortex, via the vagal nerve, to the cardiac pacemaker neurons (Figure 2.3; also see Reynolds & Richards, 2007). When the arousal system is active, reciprocal connections between the two arousal neurotransmitter systems and the cardioinhibitory centers results

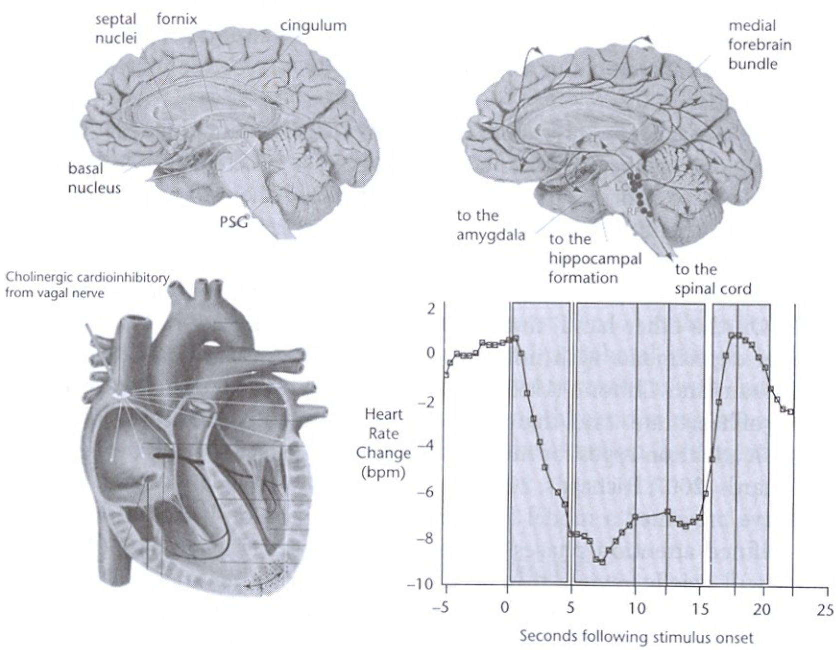

Figure 2.3. The cholinergic (upper left) and noradrenergic (upper right) neurotransmitter systems of the brain. These systems have ascending influence on the brain, and descending influence on the cardiac pacemaker cells of the heart. Heart rate changes in infants reflect the arousal properties of these neurotransmitter systems. (See also figure in plate section.)

in a large heart rate deceleration in infants.Thus, the initial heart rate deceleration occuring, defining stimulus orienting, marks the onset of the brain arousal system; the continuing lowered heart rate marks a sustaining of the brain arousal; and the return of heart rate to its prestimulus level represents the end of the brain arousal processes. Thus, one might use the terms "attention-holding," "sustained attention," "arousal," and "attentiveness" to refer to the enhancing aspect of this neural arousal system. "Attention termination," "inattention," and "inattentiveness" refer to the times when this arousal system is inactive.

INFANT AROUSAL AFFECTS SPECIFIC BRAIN ATTENTION SYSTEMS: DIRECT BRAIN MEASURES

"Now I say, 'The way to the head is through the hand.'" Keen, 2008

The first three sections of this chapter reviewed behavioral and psychophysiological studies showing that infant attention consists of multiple phases, controlled by different processes, which have differing levels of information processing. This research was consistent with the conclusions of Cohen (1972) and his evaluation of the significance of his research. The prior section reviewed a model of the neural control of these attention phases. The "functional" part of this model is based on psychophysiological recording, an understanding of the neural control of the physiological indicator of attention, and the demonstration that behavioral processes are differentially affected by the status of attention as measured by the physiological measures. The "neural" part of this model is based upon work with animals, inferences about the physiological system used to measure attention, and the behavioral tasks. These make a coherent explanation of the neural basis of attention. However, they lack direct measures of brain activity. This section will review the effect of the attention phases on direct measures of neural activity. It will also present the first attempts to localize where "inside the baby's head" these effects take place.

Researchers interested in infant cognitive processes often place their work in the context of neural control of behavior. These models often use "marker tasks" for measurement of neural activity rather than direct measures ("The way to the head is through the hand."—Keen, 2008). Marker tasks are behavioral tasks that have been studied in animal models or invasive preparations, and which have known neural control (Johnson, 1997; Richards, 2001, 2007; Richards & Hunter, 2002). Developmental changes in these behavioral tasks should reflect developmental changes in the brain area(s) that control their functioning. Marker tasks are therefore useful in "developmental cognitive neuroscience" models of behavior development. However, these measures, including psychophysiological measures such as heart rate, only provide indirect measurement of brain activity. There are several reasons to be cautious about the use of these tasks in neurodevelopmental models of attention (Richards, 2001, 2007, 2010; Richards & Hunter, 2002).

One psychophysiological measurement provides a direct measure of neural activity: the electroencephalogram (EEG), or scalp-recorded event-related potentials (ERP). The EEG is measured as electrical potential changes on the scalp, and ERPs are EEG activity that is time-locked to experimental events or cognitive processes. This electrical activity on the scalp is generated by extracellular neural tissue and neural synaptic potentials, probably excitatory post-synaptic potentials. There are times when a large number of neurons in a small area of brain tissue fire relatively synchronously, and the neurons are oriented in the same direction in relation to the skull. When this occurs, the current generated by the synaptic potential summate and current flows through the cortex, cerebralspinal fluid (CSF), meninges, skull, and skin, and can be measured as changes in electrical potential on the scalp. These are what EEG is measuring. Therefore, the EEG is a direct measure of the temporal flow of underlying neural activity, and the extent of synchronized neural activity occurring in discrete brain areas.

I, along with colleagues Greg Reynolds and Mary Courage, have a series of studies showing the effect of the heart-rate-defined attention phases on infant ERP. These studies used "oddball" tasks first used with infant participants by Courchesne (1977, 1979; Courchesne, Ganz, & Norcia, 1981) and later modified by Nelson and colleagues (e.g., Nelson & Collins, 1991, 1992). In the oddball procedure, one stimulus of a brief duration (500 ms) is presented relatively frequently ("standard stimulus") and a second stimulus is presented infrequently ("oddball"). In adults, the presentations result in a positive-going ERP component about 300 ms following stimulus onset (P300, or P3), which is larger to the oddball than to the standard stimulus. The studies with infants do not find the P300, but instead report a large negative ERP component occurring about 500 ms following stimulus onset, located primarily in the frontal and central leads, which is larger to the oddball stimulus. This has been labeled the Nc ("negative central") component. A modification of this procedure is to present a familiar stimulus frequently, a familiar stimulus infrequently, and a series of novel stimuli that are presented infrequently (Nelson & Collins, 1991, 1992). In this case, often the infrequent and frequent familiar stimuli show the same Nc response, and the infrequently presented novel stimuli result in a larger Nc response. Figure 2.4 shows the ERP recording from this procedure (Reynolds, Courage, & Richards, in press). The infrequent familiar and infrequent novel stimuli resulted in a similar magnitude Nc component peaking about 300–400 ms following stimulus onset, and a sustained Nc for the infrequent novel stimulus lasting for another 200 to 300 ms. The Nc is thought to be a measure of orienting toward the stimulus, based upon a primitive recognition memory system discriminating the familiar and novel stimuli (Nelson, 1994; Richards, 2003).

We (Reynolds & Richards, 2005, 2007; Reynolds, Courage, & Richards, in press; Richards, 2003; also see review by Reynolds & Richards, 2007) have modified this procedure to study the heart-rate-defined attention phases. As described in a prior section, for other studies (Richards, 1997) we first present a stimulus that elicits the heart rate changes marking stimulus orienting,

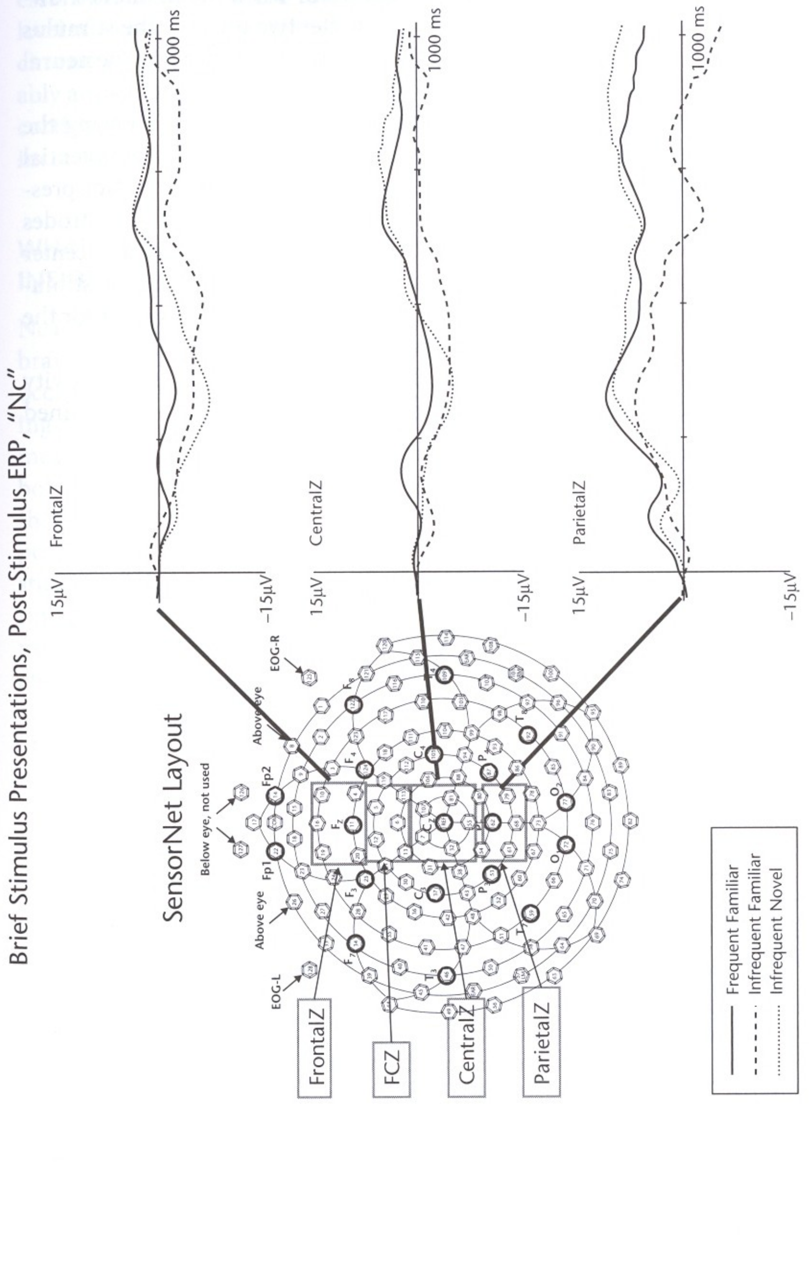

Figure 2.4. Event-related-potentials (ERP) from 4.5- to 7.5-month-old infants, as a function of electrode recording location (front of scalp, center of scalp) and brief stimulus presentation type (frequent familiar, infrequent familiar, infrequent novel).

sustained attention, attention termination, and inattentiveness. We have used both Sesame Street and an interesting visual background to do so. The attention-eliciting stimulus is then regularly replaced with the presentation of a brief geometric pattern (500 ms) that is then followed by a continuation of the underlying attention-eliciting pattern. This is continually presented, and provides a number of brief presentations that occur when the infant is showing sustained attention to the stimulus or is inattentive towards the stimulus (attention termination, inattentiveness). From this, we can measure the neural activity via EEG (and ERP) in relation to the arousal state of the brain.

Figure 2.5 presents some scalp topographical potential maps showing the effect of attentiveness on the Nc (Richards, 2003). The topographical potential maps take the ERP at a specific point in time (e.g., 500 ms, or peak of Nc), present the electrical potential level as a color, and interpolate between the electrodes with color shading. The large negative activity spread over the front and center of the scalp in the top three maps of Figure 2.5 are the Nc when the brief stimulus was presented during attention. This activity is small or nonexistent for the Nc when the brief stimulus was presented and the infant was inattentive.

How is this interpreted in light of the direct measurement of neural activity with ERP, and the brain arousal system measured with the heart-rate-defined

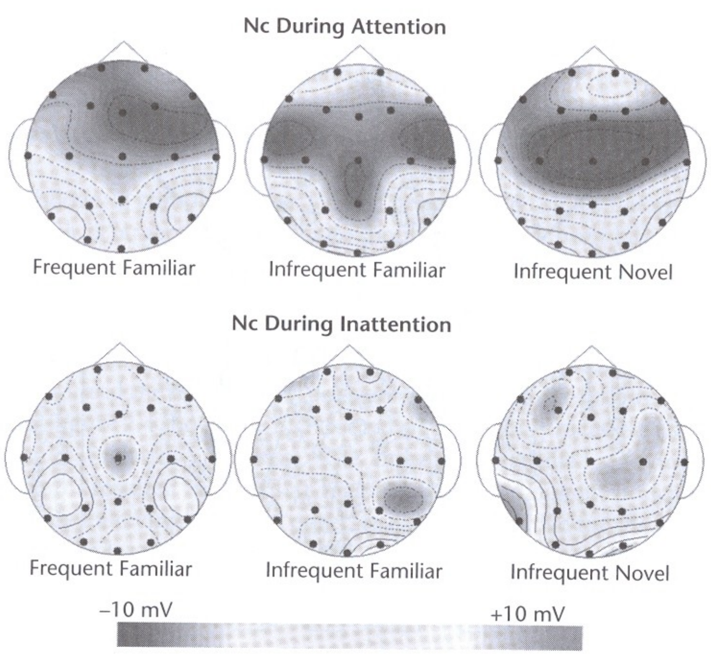

Figure 2.5. Topographical scalp potential maps as a function of brief stimulus presentation type and attention phase (top figures: attentive; bottom figures: inattentive). *Source*: From "Attention affects the recognition of briefly presented visual stimuli in infants: An ERP study," by J. E. Richards, 2003, *Developmental Science*, 6, p. 319. Copyright 2003 by Wiley-Blackwell. Reprinted with permission. (See also figure in plate section.)

sustained attention? The interpretation of the attention is implied from the interpretation given in the previous section. The neurotransmitter systems controlling arousal are active, leading to an increased amount of the noradrenergic and cholinergic neurotransmitters being present in the cortex, leading to enhanced brain activity. The amplitude of the ERP is not interpreted as necessarily indicating "more" brain activity, though it might. Rather, the higher level of electrical potential measured on the scalp likely reflects increased synchronization of the activity at specific locations in the cortex that are suitably aligned to have current flow reach the scalp. Thus, it is not just that more cortical activity occurs when the arousal system is active, but that there is an increased efficiency of specific neural locations during this arousal.

WHAT'S INSIDE A BABY'S HEAD? OR, WHERE IS ATTENTION INSIDE A BABY'S HEAD?

Nearly all developmental psychologists acknowledge the importance of the brain in influencing behavior. It is also acknowledged that developments occurring in the brain in young infants may be largely responsible for causing behavioral development. However, as a field we have been content with measurements of brain activity outside the head (direct measures) or on the body (marker tasks) and have used such measurements to infer what is inside the head. This has changed! The field of infant attention has moved to incorporate models from neuroscience, neural development, and neuroimaging, to study attention. Behavior has not been left behind—rather, changes in attention behaviors are now explained with developmental changes in the brain, neural processes, or the reciprocal effect of neural development with experiential input. These models are often labeled "developmental cognitive neuroscience." My most recent work has been to use MRI neuroimaging to measure brain structure inside the head, and relate this to neural activity measured with outside-the-head measures.

I recently summarized two ways in which information has been obtained to study brain development in infants (Richards, 2010). This information primarily comes from nonhuman animal models of brain development, primarily primates. The majority of our knowledge of the patterns and characteristics of brain development comes from the study of normally developing nonhuman animals. An advantage of this approach is that invasive neural techniques and rigorous experimental control may be used with nonhuman animals that cannot be used with human infants. However, a strong disadvantage to this approach is that it assumes a correlation can be made between ages of nonhuman animal and human infants, that changes in the brain are isomorphic across species and across brain areas, that psychological processes and the changes in these are similar in human and nonhuman animals, and that the complexity of the human brain does not affect the comparability of either brain or behavior development in human and nonhuman species. I assert that each of these disadvantages could enormously affect our neurodevelopmental models, and, unless we have some direct measure of brain development in normal human infants, we cannot know to what extent such incompatibilities exist within nonhuman-animal-model-derived neurodevelopmental models of infant cognitive processes.

The second source of information comes from postmortem studies of young infants. The most well known of these studies is a series of autopsy studies by Conel (1939–1967), who studied the human cerebral cortex. Conel laid out a well-articulated pattern of neuroanatomical and cytoarchitectural change in human infants. Conel's work is more applicable to humans because he used humans, but it has weaknesses. Longitudinal growth patterns cannot be studied in postmortem studies, it is assumed that the individuals measured at different ages are representative of normal individuals, studies are limited to small samples, and it is not always clear that the cause of death is entirely unrelated to psychological or behavioral changes that may have occured. Notwithstanding any benefits or deficits that the study of postmortem human infants, or invasive studies with nonhuman animals, may bring, both techniques fail to provide the neurodevelopmental status of any particular human infant. Thus they cannot be used to relate the status of that infant's brain development to the infant's behavioral–developmental status.

I have been using structural (anatomical) MRI with human infants who also participate in psychophysiological studies of attention (see presentation in Richards, 2010). The information obtained from the specific individual's neurodevelopmental status can be compared to neural activity measured with the EEG/ERP, or behavioral indices of development (novelty preference). This allows us to "look inside the baby's head" directly for information about brain control of cognitive processes. I have described this work in several places (Reynolds & Richards, 2009; Richards, 2007, 2010).

My use of the structural MRI scans has been to determine the location in which attention is affecting the Nc ERP component in the modified oddball tasks. I previously described the effect of the heart-rate-defined sustained attention on the Nc ERP components as likely reflecting the increased synchronization of the activity at specific locations in the cortex. These locations encompass enough cortical area, and are suitably aligned, to produce an electrical current that flows through the materials of the head to the scalp. A technique called "cortical source analysis" (brain electrical source analysis; Reynolds & Richards, 2007, 2009; Richards, submitted) uses the amplitude and topographic distribution of the EEG on the scalp to infer the brain area(s) that generate the electrical current. The location of the current source and the activity of the current source over time may be calculated.

The steps in this analysis using the structural MRI are as follows: First, the structural MRI scan is done. Figure 2.6 (upper left) shows a single slice of an MRI volume taken from a 7.5-month-old infant. Second, the MRI volume is segmented into component parts, such as gray matter, white matter, CSF, skull, scalp. Figure 2.6 (left, middle panel) shows the areas from the MRI slice with colors representing the segmented material. Third, a computer file is made, called a "wireframe," that consists of tetrahedra mapped with the location and material type for the entire head (Figure 2.6, bottom left). Finally, the

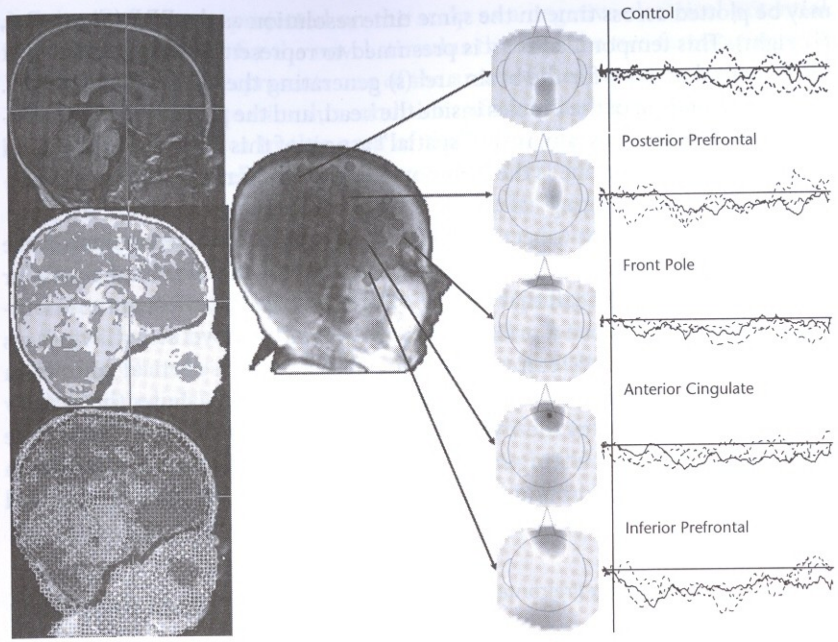

Figure 2.6. Cortical source analysis of the Nc ERP component with realistic models of infant heads via structural MRI of infant participants. The left figures represent steps in the cortical source analysis technique, the mid-left figure potential cortical source locations for the Nc, the mid-right panels the topographical potential maps for the projection of the sources on the scalp, and the right panels the temporal activity of different brain areas for the brief stimulus presentation types. (See also figure in plate section.)

wireframe file may be used with computer programs to do the cortical source analysis. This aspect of this work is "neuroimaging."

Figure 2.6 shows some results from a study of infant recognition memory using the modified oddball procedure (Reynolds, Courage, & Richards, in press). The head with spots on it is a representation of the saggital view of the likely locations for the current sources of the Nc ERP component. These locations were identified with the cortical source analysis of the ERP in the modified oddball task. The locations have been grouped into distinct neuroanatomical areas, including inferior prefrontal, frontal pole, anterior cingulate, posterior-superior prefrontal, and central. The dipoles identified by the cortical source analysis then may be used in a quantitative model to generate current that is projected to the scalp surface, and drawn as topographical scalp potential maps. The column of topographical scalp potential maps shown in the right middle section of Figure 2.6 represents these projections from the dipoles in the specified areas onto the scalp. The topographical potential maps from the inferior prefrontal and anterior cingulate match the topographical scalp potential map of the ERP in this study, and, to a lesser extent, so does the posterior-superior prefrontal projections. Finally, the activity of the dipoles

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from adult participants. This requires the application of cortical source analysis with realistic head models from infant participants (Richards, submitted). It also is the case that infant head media differ from those of adults. For example, the impedances of skull and scalp are much larger in adults than in infants, and a substantial portion of the axons are unmyelinated at birth. The realistic models being used with the MRI recording will allow tests of the effect that these parameters have on cortical source analysis for infant participants. We believe that a large library of structural MRIs done on human infants, the "NIH MRI Study of Normal Brain Development" (Almli, Rivkin, & McKinstry, 2007; Evans, 2006; NIH, 1998) may provide the raw material for examining the characteristics of the head media in infants, and stimulate work that relates brain development in individual participants to the development of attention, perception, cognition, and behavior.

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