

Prospectus for Recording EEG and ERP in Infants

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Infant Cognitive Psychophysiology

Psychophysiology may be defined as "the study of relations between psychological manipulations and resulting physiological responses, measured in the living organism, to promote understanding of the relation between mental and bodily processes"¹. The main impetus of psychophysiology is to relate psychological behavior to underlying physiological systems. Psychophysiology is also the study of parallel relations between psychological behavior and physiological systems. Psychophysiological research typically uses non-invasive recording methods and human subjects. Other scientific areas, such as physiological psychology, psychobiology, and behavioral neuroscience study physiological-psychological relations. These fields use more invasive physiological measures and, as a result, use animal models rather than human subjects in the study of behavior.

Cognitive psychology is the study of behavior such as attention, memory, information processing, thinking, and language. Cognitive psychophysiology uses physiological functions to study these functions. Cognitive psychophysiology sometimes merely uses physiological systems in the study of cognitive psychology. Many cognitive psychophysicists are interested in how physiological systems (e.g., brain, central nervous system, autonomic nervous system) affect cognitive behavior. Researchers interested in infant cognitive development have turned to psychophysiological theories and methods to aid their study.

There are several sources for the review of infant cognitive psychophysiology. The reader may consult other sources for reviews of infant developmental psychophysiology^[2,3], as well as reviews of the development in infancy of specific systems (e.g., EEG/ERP^[4,5,6,7,8], Heart Rate^[9,10,11], Sustained attention^[12,13,14,15,16,17,18,19]).

The present paper will present recording and quantification techniques for recording EEG and quantifying ERP's in infants. These will be for the purpose of planning and detailing how these EEG/ERP will be recorded in a series of studies by the author on infant attention and infant recognition memory. A brief review will be given of work by Hillyard, Mangun, and associates showing the localization of early spatial selective attention effects in the ERP, a review of presaccadic activity occurring in the EEG potential, and a brief review of some research on infant evoked scalp potentials in recognition memory will be presented. These reviews serve as the background for the recording of ERP's in a covert spatial attention task in infants, and in examining ERP responses to familiar and novel visual stimuli as a function of central attention processing in infants. Some data from studies of the author will be presented to illustrate how these studies will be done.

EEG and Event-Related Potentials (ERP)

The study of electrical potentials measured with surface electrodes on the scalp in infants has a long history. There have been two main trends of research. One trend has studied spontaneous electrical activity measured on the scalp, the "electroencephalogram" (EEG). Scalp EEG consists of small voltage changes that are caused by action potentials summed over large numbers of neurons, synapses, or neural pathways. The neural activity that is recorded is primarily in the cerebral cortex and in thalamocortical connections. Perhaps the most frequent use of spontaneous EEG has been the patterns of potentials that occur in different sleep states. EEG in sleep states has been studied extensively in newborn and infants. The characteristics of EEG in sleep and waking states is an essential component of the definition of sleep states in infants.

A second trend of research is the study of scalp electrical activity that occurs in response to stimulus challenge, "evoked scalp potentials". These are averages of the EEG and are time-locked to specific psychological events, e.g., event-related-potentials (ERP) or evoked potentials (EP). The evoked scalp potentials have an important advantage over EEG in the study of infant cognitive behavior. Stimuli and experimental manipulations known to have significant psychological consequences may be studied with the evoked EEG at the same time the psychological process is occurring.

Scalp potentials are measured with small electrodes placed on the scalp at specified locations. The electrode placement is typically done according to an accepted system, e.g., the "10-20 System" in which electrode placement occurs over the frontal, central, temporal, parietal, and occipital portions of the scalp^[20]. The 10-20 System has 19 electrodes. Recently, electrode recordings of "high-density" have been developed, such as 40 electrodes^[21], or 64 or 128 electrodes^[22,23]. The electrical potential measured at each location is measured in reference to a common electrode placed on the body near the scalp that does not have electrical activity occurring as a result of brain activity (e.g., ear or ear mastoid). The electrical activity measured on the scalp is generated by the electrical activity of groups of neurons in the brain, summed over large numbers of neurons and synapses. The amplitude of the electrical potential measured at the scalp in infants ranges from 0.1 mV to 20-30 mV.

Spontaneous EEG consists of constantly varying electrical potentials that occur under a variety of stimulus conditions. However, psychophysicists are interested in brain activity occurring as a result of psychological processes. Thus, EEG activity synchronous with externally observable events, and thought to be occurring simultaneous with psychological activity, is of most interest. These scalp potential changes are labeled "event-related potential" (ERP). The EEG may be time locked to specific psychological or experimental events and averaged over multiple trials, resulting in averaged event-related-potentials (ERP). The ERP has varying positive and negative electrical waves labeled components. These components are hypothesized to be related to specific cortical events. These cortical events in turn are 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^[6,24,25,26]. For example, early components of the ERP (P1, N1, P2, N2) represent activity in the first cortical areas to receive sensory input (e.g, occipital areas V1 and V2 for visual stimuli). The later components of the ERP (e.g., P300 or N400) represent processing of information at more advanced cognitive

levels, such as a shift of attention, context-updating, orienting, or surprise to a relatively novel stimulus (P300, or P3) or the resolution of a semantic ambiguity at the end of sentence processing (N400, or N4).

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

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

Insert Figure 1 about here

Also, include Figure 1 from Hillyard et al, 1995

Most of the ERP research with infants has been with exogenous ERP components. These studies have used simple stimuli and experimental conditions to elicit the evoked potentials. This methodology is useful for the study of sensory processing and for understanding how the developing infant processes the psychophysical properties of sensory stimuli. This approach may also be extremely useful in the understanding of how cortical maturation is reflected in the ERP components in the early phases of information processing^[4,8]. Reviews of such work can be found in Courchesne^[4], Kurtzberg et al.^[5], Nelson^[6], Salapatek and Nelson^[7], Vaughan & Kurtzberg^[27,8], among others.

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

There are both benefits and difficulties in the use of ERP in the study of cognitive neuroscience. The benefits include its high temporal resolution, its noninvasive nature, and its recording of large neuronal populations^[26]. The time course of the EEG or ERP occurs at the same time course as individual cognitive processes. This makes the EEG/ERP valuable for online monitoring of individual cognitive processes and facilitates inferences about the timing of cognitive processes. These processes cannot be measured with positive emission tomography (PET) or functional magnetic resonance imaging (fMRI), which have a time resolution in the minutes or tens of seconds, rather than milliseconds. EEG recording is noninvasive and safe. This is crucial for studying special populations, such as normal infants and children, who may not be amenable to PET study because of the need for injections of radioactive tracer elements. Also, the methodology of recording EEG is not detrimental to the experimental requirements of cognitive study, and does not interfere with typical cognitive experiments. This is in contrast with fMRI recording in which high magnetic fields and confinement precludes many types of cognitive psychology studies.

There are at least two difficulties associated with traditional EEG and ERP use in cognitive psychology and cognitive neuroscience. First, the EEG/ERP has poor spatial resolution for identifying cortical sources thought to be responsible for cognitive activity. The International 10/20 recording system^[20,28] (10-20 has 19 electrode locations F_Z, P_Z, C_Z, Fp₁, Fp₂, F₃, F₄, F₇, F₈, C₃, C₄, T₃, T₄, P₃, P₄, T₅, T₆, O₁, O₂; and often non-10/20 electrode, O_Z). This configuration has an interelectrode distance (~ 5 cm average interelectrode distance) that makes it difficult to obtain spatial resolution of better than several cm and give the impression of a smooth ERP surface when miss high spatial frequency ERP components^[29]. Second, the techniques for identifying cortical sources of ERP components involve recording on the scalp surface and hypothesizing cortical generators (cortical dipoles) that account for the scalp topographical distribution. This technique has a basic indeterminacy in that many possible solutions for the obtained scalp potential topography exist and there are no algorithms for choosing a mathematically-definitive unique solution^[30,31,26]. Thus, inferring the underlying cortical activity from scalp recorded EEG/ERP may not be unequivocal with this technique.

Three recent developments have improved the applicability of EEG/ERP recording for cognitive psychology and cognitive neuroscience^[30,31,26]. First, High-density EEG/ERP recording has partially solved these problems. The problem of spatial localization may be partially overcome by sampling electrical potential changes at higher densities than the International 10-20 system. One such recording configuration is the "geodesic net" developed by Don Tucker (Electrical Geodesics Inc^[22,23]). These nets have 64- or 128-electrode configurations and provide interelectrode distances of 35 to 40 mm or less^[22]. Figure 2^[29] shows the sensor layout of the

geodesic net with the approximate positions of the 10-20 system superimposed. This may allow identification of scalp topographic sources to 0.5 cm locations and greatly aids in the localization of cortical source generators. Second, better quantitative techniques along with the higher-density recording strategies allows the quantitative estimation of source dipoles. Scalp current-density topographical mapping^[32,33,34,35] allows the visualization of current densities on the scalp that localizes the source currents for the potential changes recorded with EEG (or ERP). This allows better spatial resolution of local cortical sources reflected on the scalp topography. Techniques using dipole modeling (e.g., "brain electrical source analysis"^[36,37,38,39]) have been improved over early versions. These hypothesize specific locations for neural generators (cortical dipoles, source potentials) of the recorded cortical potentials, and compare with cortical potentials. These algorithms are now more sophisticated and do not suffer the indeterminacy of the 10-20 system and are widely available in computer programs. Finally, a reasonable trend in current cognitive psychophysiology has been the complementary use of multiple recording techniques. For example, functional neural imaging with PET or fMRI may be combined with high density EEG/ERP recording to provide detailed spatial localization of a process (PET, fMRI) with high temporal resolution (EEG/ERP) to provide a detailed picture of the cortical generator and its close relation to the psychological process being studied. Similarly, structural MRI recording or identification with neuropsychological tests of cortical lesions may be used to identify specific cortical locations to be examined, and then cortical dipoles are hypothesized that are constrained by the MRI or neuropsychological information and the high density ERP recording is used to confirm the involvement of this area in the cognitive process. An example of this combination of high density recording, structural MRI recording, and source localization may be found in the identification of the cortical sources of the P1 "validity" effect in spatial cueing and covert attention^[25,40,41].

Insert Figure 2 about here

Measurement and Quantification of EEG.

Microcomputer PC Hardware. The electroencephalogram (EEG) is a small electrical potential recorded on the scalp. In infants it may range from 0.1 mV to 20-30 mV. The EEG needs to be amplified. The EEG in the present studies will be recorded with a Grass Neurodata Acquisition system. This system has individual AC amplifiers with bandpass (low-pass and high-pass) filters, and amplifier settings. The individual AC amplifiers for the EEG are set to a common bandpass and amplifier settings because of the similarity of the signal across scalp recording sites. Currently, we have 40 channels (24- and 16-channel configurations) of amplifiers. In most of the studies there will be 32 channels being used exclusively for EEG recording and 8 channels being used for ECG (AC amplifier), horizontal EOG (DC amplifier), vertical EOG (AC amplifier), and respiration (DC amplifier). The EEG amplifiers will have band-pass filters set at 0.1 to 100 Hz, and 20K amplification, and a 60 hz notch filter will be used to eliminate line interference.

The EEG is digitized from the amplifiers with analog-to-digital sampling techniques. The amplified signal from the Neurodata Acquisition System is +/- 5 volts. This is converted by microcomputer analog-to-digital (A/D) boards and stored in a computer on a fixed disk. The EEG will be digitized with one Data Translation AD3003 A/D board in a Dell Workstation 610 computer (32 channels) and an A/D boards in a second Dell Workstation 610 computer. Each board can sample 32 channels of analog information and have a conversion rate of approximately 5 μ s (microseconds). The channels are converted sequentially and thus require approximately 160 μ s for the conversion of the entire 32 channels on one board. For convenience (rather than necessity) the A/D board in the computer samples the 8 non-EEG channels (ECG, EOG, respiration).

The A/D board in the Dell computers have timer/counter clocks that can count at several MHz. The MHz timer is linked to counters that count down from a fixed value to 0 every 1 ms. At the end of the count the A/D board hardware executes the sampling necessary for the channels. The count-down to 0 on the board also generates an interrupt and a computer interrupt service routine is executed. The interrupt service routine keeps track of a software clock that is accessible to all of the laboratory computer programs. This clock is used to time experimental events, to time ECG and HR (R-R intervals), and to synchronize all laboratory events (experimental protocol, videotape time code, physiological signals). The interrupt service routine also checks a "First-In-First-Out" buffer and stores any acquired digitized values to memory, which is later saved to disk for further offline processing.

At the end of the timer/counter countdown in the A/D board in one of the Dell computers an electrical pulse is generated. This pulse is electrically linked to the A/D board in the second computer. Those boards are set up so that the A/D board hardware executes its channel samples at the onset of this signal rather than on an internal timer/counter operation. In this manner the timing across the computers across the A/D boards is synchronized to 1 ms resolution. The synchronicity has been confirmed with a duplicate EEG channel and duplicate ECG channel recorded on the two A/D boards in the two computers. The results of this duplicate EEG recording show exact synchronization between the sampling systems. Sampling is not exactly simultaneous^[42]. However, since the time for the sampling is so small and EEG/ERP averaging is done at a much slower rate (250 Hz), the problem of sampling lags across channels is limited to 160 μ s maximum lag, far smaller than the overall sampling interval for the ERP (4 ms).

The sampling of the EEG is done by a program that collects data at 1K hz (1 msec samples) for each channel. A large amount of data is generated by the unusually fast sampling rate (1 kHz per channel). However, the data is saved to a microcomputer server that has a 18 gigabyte hard disk, and data are also stored on the mainframe (IBM MVS system) direct access storage device via internet FTP protocol allowing unlimited storage. The raw EEG data can be easily transported back and forth between the MVS computer system and the microcomputer. The analysis will be done on 250 hz sampling. This is sufficiently faster than the amplifier's upper band (100

hz) to eliminate aliasing by sampling at the Nyquist frequency (2.5 times fastest frequency). Calibration pulses will be done for each channel before and after each subject to insure the appropriate quantification of electrical potential changes across subjects.

EGI NetAmps Hardware. A relatively recent system has been developed by Electrical Geodesics Incorporated (EGI) to measure 128 channels of EEG. The EGI NetAmps system includes amplifiers for the EEG, a computer station integrated with the amplifiers, appropriate interface between the EEG amplifiers and the computer, and software for the EEG acquisition. The amplifiers for this system have a very high impedance value (200 M Ω) and are designed by EGI to accept recording input with very high impedance values (10K to 50K Ω). This allows sensor nets to be used without scalp abrasion, recording paste or gel. The NetAmps system has the computer acquisition and amplifiers integrated into a system that is easily implemented. The acquisition issues (A/D, simultaneous sample and hold, timing, number of channels, storage) are already solved with this integrated system. The EEG amplifiers will have band-pass filters set at 0.1 to 100 Hz, and 20K amplification, and a 60 hz notch filter will be used to eliminate line interference

One of the great advantages of this system is the design of the amplifiers. These amplifiers accept recording input with very high impedance values (10K to 50K Ω). Typically with EEG recording relatively low impedance values (< 5K Ω) are required. This is achieved by scalp abrasion. With relatively few electrodes (e.g., middle electrodes; or 19 electrodes of the 10-20 system), adult patients, and low-risk patients, this is reasonable. However, with 128-electrode recording, this takes too long and provides extra risk to the participants. The NetAmps use a "geodesic" recording net that contains electrodes that only require placement and do not require scalp abrasion. This is done using a saline solution for the electrical conductor. This results in electrodes with relatively high impedances, but these high impedances are matched by the NetAmps amplifiers. This results in relatively easy placement of the recording electrodes. This is critical in the use of high-density EEG/ERP recording in participants such as infants or children who do not easily take the long setup procedures required with abrasion electrodes, and for whom scalp abrasion is an unacceptable risk.

The sampling of the EEG is done on the NetAmps system by a program called "Netstation". The Netstation program will be used to sample the EEG at 250 Hz (4 msec samples) for each of 128 channels. The Netstation program provides zeroing and gain calibrations and impedance measurements on each channel. A large amount of data is generated by this sampling rate and the number of channels. The data is stored on the NetAmps PowerPC-based computer system and later transferred to a server with a 18 gigabyte hard disk, to a mainframe (IBM MVS system) direct access storage device via internet FTP protocol allowing unlimited storage, and on recordable CD disks. The raw EEG data can be easily transported back and forth between the MVS computer system and the microcomputer. The Netstation recording can get time synchronization and experimental events from the PC-based microcomputer that is running the experimental protocol. These experimental events are used in later programs to extract the EEG data based on significant experimental events, or eye movements, to be used in the averaging procedure generating the ERP data.

Visual stimuli timing. Timing in previous studies of the PI has been at the limit of the computer operating system for programs running at the "application level", approximately 30 ms. This timing was sufficient because latencies in previous studies were of the order of 1-2 s difference between experimental conditions or ages^[43,44,45], because the minimum ECG signal is approximately 350 ms and the stimulus onset could be identified in less than an IBI length, and because fixation judgements based on VCR-based recording has resolution limited to a single video frame scan (1/2 total frame length = ~ 16 ms). Ms accuracy has been important in recent studies of the PI^[46,47,48] because latencies were tied to saccadic eye movements, that can be timed with ms accuracy using EOG techniques. Ms resolution of experimental stimuli is important for the studies involving saccadic eye movements as a measure of response latency. Also, for ERP analyses timing must be done on a ms basis to accurately time stimulus onset for ERP averages. Stimulus presentation accuracy will be achieved through stimulus presentation on a hardware device that allows software control of the hardware device. The computer-generated and Sesame Street stimuli are presented through a Tecmar Frame Grabber board in the Dell Workstation 610 microcomputer. This device allows software to access the hardware video vertical blanking interval (no screen refresh) and the vertical refresh interval (refreshing occurs) of the NTSC protocol. The computer programs can determine when the blanking interval occurs (1.4 ms), when the refresh begins (1 ms resolution), and when the vertical refresh interval occurs (15.27 ms), for each half-frame (~ 16.67 ms). The computer-generated stimuli, for example, are placed into the frame grabber display memory before the trial begins with the display off. When the experimental protocol calls for stimulus onset, the frame grabber is queried until it is in the vertical blanking interval. The display is turned on during this time, and the ms that the screen refresh begins is recorded so that the stimulus begins display in the next refresh interval. From the known location of the stimulus on the TV, the number of ms necessary to reach the first display line of the stimulus can be calculated (62.5 ms per line). The display of the stimulus takes a finite interval that can be calculated. The stimuli in Experiment 2 are no more than 120 lines total, so the first set of interlaced lines takes at the most 60 * 62.5 ms = 3.75 ms. The stimuli in Experiment 3 are no more than 240 lines high, so the first set of interlaced lines takes at most 120 * 62.5 ms = 7.50 ms to display. These times are not appreciably more than the resolution of the ERP averaging interval (e.g., 4 ms for 250 Hz). For simplicity, the time of stimulus onset will be defined as the time when the stimulus first is displayed on the screen (beginning of vertical refresh interval + number of ms necessary to reach the first display line of the stimulus).

Timing and time-synchronization are also done with the Netstation recording program for the interface between the EGI system and the experimental presentation computers. The Netstation program has a ms time base that is separate from the time base of the system generating stimuli and controlling the experimental protocol. There is a serial interface between the EGI computer and the experimental computer. This interface accomplishes time synchronization by passing a time from the experimental computer to the EGI computer. The time difference between the two computers is stored in the Netstation program. During the experiment the experimental computer keeps track of heart rate timing, experimental events, stimulus timing, and video recording timing. Times at which EEG is to be taken is sent to the EGI computer and the Netstation program stores these time in the Netstation's time base by

converting the experimental computer time base to its own time base. Later, during segmentation of the EEG for the ERP averaging the Netstation computer is able to find the appropriate EEG activity for the ERP analyses.

Electrodes and recording derivation for Electrocaps. The EEG will be recorded with electrodes mounted in an elastic cap (Electro-Cap)^[49,50]. There will be three cap sizes, Electro-Cap Extra Small (46 to 50 mm), Infa-Cap I (42 to 46 mm), and Infa-Cap II (38 to 42 mm). These three caps are sufficient to cover the range of head sizes from 8 to 26 weeks of age^[46,28]. The recording cap will be filled with Omni-Prep gel that is injected into the electrodes and a light intensity rub is done^[28]. A separate recording gel is then injected into the electrodes. This is done until impedances are below 5K Ω . We have found in pilot testing that a full 10-20 derivation (+ OZ) can be done in 10-12 minutes by a skilled experimenter. We have also found that infants tolerate this hookup procedure fairly well if accompanied by a second experimenter with toys, a child "busy box", clown faces, etc.

The EEG derivations (scalp sites) that will be used are based on the "International 10-20" system^[20] and recent guidelines of the Society for Psychophysiological Research^[28] for EEG/ERP research. The "International 10-20" system identifies a set of scalp recording sites that are accepted by the scientific community for recording. The "10-20" stands for percentages from midline and lateral locations, and nasion-inion differences. There are 3 sites on the nasion-inion semi-circumference, FZ, CZ, PZ. The FpZ location (not part of the standard 10-20 leads) is 10% of the nasion-inion circumference. The FZ site is 20% further along the nasion-inion circumference, and 20% of the distance to Cz, which is on the vertex. The PZ site is 20% of the distance between Cz and the inion, or 30% of the distance between the inion and CZ. Finally the OZ site (not part of the standard 10-20 leads) is 10% of the distance between the inion-nasion circumference to the inion, and 20% from PZ. There are 16 lateral sites--sites located just-off center (Fp1, Fp2, F3, F4, C3, C4, P3, P4, O1, O2), and sites located near the presumed edges of the cortex (F7, F8, T3, T4, T5, T6). The Fp sites are 10% of the distance between the inion and nasion in the frontal pole, and the O sites are 10% of the distance between the nasion and inion over the occipital pole. The intermediate sites are located along the semi-circumference from the vertex site (Fz, Cz, Pz) at locations that are 10 or 20% of the distance from the site to the edge of the recording area. In addition to these 19 sites, a 20th site is routinely added in each--OZ, the occipital site along the midline (this site is often used in EP studies simply using the central locations--FZ, CZ, PZ, OZ--in order to sample the occipital area^[51,52,53,54,55,56,57,58]). The leads in all studies will be referred to a linked mastoid reference by recording the active leads with respect to one mastoid, recording the potential difference between mastoids, and using an algebraic re-referencing to get the average reference^[28,59,49,50]. For experiments involving infants covert attention, several locations will be recorded that may be involved in visual perception and selective spatial attention (occipital and parietal^[40,41,25,60,61,62,63,64]), and presaccadic activity (parietal, central and frontal^[65,66,67,68,69,70,71,72,73]). The recognition memory studies are primarily a replication of procedures by Nelson and colleagues^[51,58,52,53] and other infant researchers^[54,55,56,57] and will follow those studies by simply recording the central locations (FZ, CZ, PZ, OZ). The horizontal EOG will be recorded in both experiments, both for use for saccade identification and for EEG/ERP correction. Vertical EOG will be recorded with an electrode under the left eye relative to Fp1 for blink detection and for vertical eye movement corrections.

Geodesic Sensor Net derivation. The recordings for the studies are done using multiple-channel high-density recording techniques with 128 electrodes^[22]. This will be done with the "Geodesic Sensor Net" manufactured by Electrical Geodesics Inc. These recording nets have a "geodesic" configuration with sensor pedestals connected with an elastic structure. The geodesic configuration allows the stable placement of the electrodes with evenly spaced electrodes in a minimum amount of time. Each electrode is encased in a small plastic pedestal that encases an Ag/AgCl electrode and a sponge that contacts the scalp. The net is soaked in a KCl solution that is electrolytic and so gels or paste is not necessary for electrical contact. This provides impedances in the range of 10 to 50 k Ω , which may be sufficient if the amplifier has sufficiently high impedance (> 50 M Ω). This results in a high impedance between electrodes (10K to 50K Ω) compared to traditional recording standards (e.g., < 5K Ω). The NetAmps system has amplifiers that are matched to this impedance level, so the NetAmps system along with the geodesic sensor nets provide a suitable system for high-density EEG recording.

The geodesic sensor nets have several advantages over traditional 10-20^[20,28] recording montages. First, 10-20 recording with electrode gel or paste, used with low impedance amplifiers (e.g., Grass Neurodata Amplifiers) require low impedance values. This is achieved by scalp abrasion. This scalp abrasion is difficult to do, may be intrusive for special populations such as infant participants, may result in significant health risks (AIDS, hepatitis) to participants^[74], and takes a long time to complete. Traditional recording of EEG for ERP studies has typically involved only a few electrodes (e.g., midline Fz, Pz, Cz, Oz locations; or parietal-occipital locations Pz, P3, P4, T5, T6, O1, O2 OZ) or the 19 electrodes of the 10-20 system^[20,28] Fz, Pz, Cz, Fp1, Fp2, F3, F4, F7, F8, C3, C4, T3, T4, P3, P4, T5, T6, O1, O2; and non-10/20 electrode, OZ). As long as the electrode number was about 20 or less this was acceptable. However, high-density recording techniques are necessary for appropriate spatial frequencies to be determined for cortical source localization procedures^[35,29,22,23]. The 10-20 system has an average interelectrode distance of about 50 mm and makes it difficult to obtain spatial resolution of better than several cm and give the impression of a smooth ERP surface when miss high spatial frequency ERP components^[29]. The geodesic sensor nets have average interelectrode distances of about 35 mm for adults and as small as 21 mm for infants with 128 electrodes. Figure 2 shows the configuration of the "geodesic net" and a superimposed 10-20 system montage. The geodesic sensor nets require only saline for electrical conduction, and so may be placed on participants in about 10 minutes. This makes them suitable for high-density EEG recording in some groups that would not otherwise be amenable to high-density EEG/ERP recording (e.g., infant participants, or high-risk participants such as older adults).

There are 64- and 128-electrode caps for adults and infants. The 128-channel nets will be used for the studies to be done. The adult and infants nets use an electrode at the vertex location for a reference and this electrode pedestal is marked. The placement of the nets

is done by locating the vertex and positioning the vertex electrode participant's vertex. The rest of the net, configured by the geodesic geometry, is then positioned in appropriate locations. There are markers for the two ears and the nasion. The 128-channel infant nets have three characteristics different from the adult nets. First, the nets are constructed with AgCl-plated conductive carbon pellets and carbon fiber wires. The electrode assembly has a smaller size and weight than the traditional metallic wires with Ag/AgCl electrodes and thus the electrodes are considerably smaller. The carbon fiber wires are not as flexible as the traditional metallic wires so that some care needs to be taken to keep the infant still and the cabling stable with an electrode mount. However, the lighter wire eases the tension on the electrodes relative to the typical metallic wires. Second, the pedestal is smaller and interelectrode distance is smaller. The interelectrode distance on a 64-channel adult cap is about 35 to 45 mm. The interelectrode distance on the 64-channel infant net is 31 mm, and the interelectrode distance on the 128-channel infant net is 21 mm. The 21 mm interelectrode distance is well below the recommendation that a maximum of 30 mm be used for high-density recordings to resolve the focal electrical potential changes, sharp field gradients, and provide an adequate average reference^[29]. Third, four of the electrodes near the eyes are not included on the net. These include the two electrodes at the outer canthii of the eyes and the two electrodes at the bottom of the eyes. Thus, there are no electrodes that cover the infant's face. Separate electrodes are used with adhesive electrode collars are placed at these locations and inserted into the mount holding the wiring of the net. These electrodes around the face are bothersome to infants and could not be placed on the infant in the typical sensor net configuration.

We have tested the 128-channel caps on infants and have found them to be excellent. The 64-channel have been used successfully on three-month-old infants^[75] and six-month-old infants^[76,77], as well at other ages^[78,79]. We have tested the 128-channel caps on about 20 infants (as of July, 2000). The setup time for these caps is less than 10 min, compared to a 10-15 min preparation for the 19 electrodes of the 10-20 system that the author has done^[21,80] or a 15-20 min preparation for a 40 electrode configuration^[81]. Infants show about the same amount of fussiness during the entire procedure as they do during the initial fitting of the Electrocap caps. However, after this initial fitting the EGI sensor nets get positioned very easily in distinction to the tedious filling of gel and abrasive in the Electrocap caps. One person distracts / entertains the infants with toys while the other experimenter adjusts the pedestals. We have had no problem placing the nets on the vertex, locating the markers over the ears, and placing the nasion electrode on the nasion. The spacing of the pedestals with the geodesic elastic connections worked well. We anticipate almost no attrition due to the placement of the electrode nets on the infants. The experimental procedures that we use keep the infants fixation towards the television monitor displaying stimuli. The positioning of the wires, the electrode mount, and the wall-mount articulated arm to hold the cabling keep the wires in a position above and behind the infant's viewing area so that this equipment is not noticed by the infant.

Calculation of ERP and Topographical Mapping

Event-related-potential averages. EEG will be examined before ERP averages for horizontal and vertical eye movements and blinks. The EOG artifacts will not automatically be rejected. The trials containing eye-movement artifact, defined as voltages in excess of 150 mV in the EOG, will be rejected for any further analysis. In infants, the ERP's tend to be much larger than adults and the eye movement artifacts are not as severe. Nelson^[6] for example, reports that blinks as large as 250 mV have negligible effects on the infant ERP. Epochs containing eye movements that are unrelated to the experimental manipulations (e.g., saccade in stimuli in recognition memory experiments) will use methods that statistically partial out EOG activity in the frequency domain^[82,83,84] or time-domain^[85,83]. These techniques will be applied to the ERP only for those trials on which significant saccades are identified^[6]. Epochs containing eye movement that are related to the experimental manipulations, e.g., a saccade to the "competing" stimulus in studies of covert attention, or the saccade to the peripheral stimulus, will be excluded from the ERP analyses.

The ERP averages will be made from 250 ms intervals sampled from the 1 ms EEG recording. The 1 ms EEG recording will be digitally filtered with a 0.1 to 30 Hz bandpass, since the speed of the signals for the ERP averages are in this range. The ERP's will be constructed from relevant experimental conditions for a single subject, as well as "grand means" across all subjects in a specific experimental condition. The mean EEG level for the 100 ms before the event will be subtracted from the EEG levels following the event.

The latency of the ERP components will be done with "peak-picking". The mean voltage within a specified latency window (e.g., P1, N1, P2, N2), relative to the mean prestimulus voltage, will be examined and ERP latency will be defined by the time point of the maximum peak within that window^[49,50]. Mean amplitude and peak latency initially will be examined for relevant peaks in adult durations (e.g., Table 1 in Luck & Hillyard^[49], P1 is 50-150 ms, P2 is 150-300 ms, N2 is 175-300 ms), though it is expected that the peaks will occur later because of the difference between infant and adult component latencies^[86,87,88,8]. It is expected that the very early components (e.g., P1, N1) may occur as late as 200-300 ms at the youngest ages^[89,88], whereas by 6 months these components should be occurring at earlier latencies but still will be delayed relative to adult latencies^[86,89]. The author's work^[21] has shown a positive ERP component occurring around 135 ms that responded to spatial cueing parameters as the adult P1, and a negative ERP component occurring at about 260 ms that also was responsive to spatial cueing parameters, suggesting this as an "N1" component.

Repeated-measures ANOVA will be the analysis method for the raw data^[90,49,50]. These will be analyzed with repeated-measures analysis of variance, using e-correction procedures for non-sphericity in the repeated measures^[91,92].

Scalp potential and current source density. Topographical mapping techniques will be used to identify possible brain sources. For these analyses, the scalp potentials will be re-referenced to an average reference and interpolations will be done for topographical mapping using a third-order spherical spline technique^[90,34,33,32]. Both scalp potential maps and current source density (CSD) maps will be computed on these interpolated data. The scalp potential maps show the distribution of actual scalp potentials across points in time.

The CSD maps show the direction from where current emerges from the brain (sources) and enters from the scalp into the brain (sinks). The CSD maps have some advantages in that they are less dependent on reference electrode site, show sharper distributions than potential maps, increase the spatial resolution of the topographical maps, and reflect mainly the activity of cortical generators.

The topographical mapping technique will use meridian maps based on geographical mapping techniques^[93]. These maps will be adjusted for the head size parameters of the individual infants, or groups of infants, making up the ERP averages. This is done by measurement of several head sizes, including the nasion-vertex semi-circumference, the vertex-inion semi-circumference, the mastoid-vertex-mastoid semi-circumference, the nasion-mastoid-inion-mastoid circumference, the nasion-inion radius, and the mastoid-mastoid radius. These measurements give the dimensions for the head. The exact three-dimensional position of the electrodes on the Geodesic Sensor Net and the head measurements gives the shape of the sphere for the topographical map. The points on the Geodesic Sensor Net are mapped in Euclidean space onto a representation of the scalp, using "geographical" mapping coordinates and the head measurements. ERP and CSD maps (spline maps, etc) are constructed with the geographical mapping programs to display information in a summary manner on these maps.

An example of the use of topographical scalp maps for illustrating ERP effects comes from a recent study of presaccadic ERP in young infants^[81]. In this study 20-week-old infants were presented with a cue that indicated where a target would occur. The target occurring in the same location as the cue could lead to the infant expecting its occurrence in that location and engaging in a planned saccade to that location^[81,94]. The ERP immediately preceding the occurrence of the saccade, the "presaccadic ERP", is shown in Figure 3. There was a positive presaccadic potential (PSP 50 on figure) occurring about 50 ms before the saccade that occurred primarily over the frontal cortex, as well as a presaccadic potential (PSP 300) that occurred on about 300 ms before cued trials. It is believed that this saccade planning involves the frontal eye fields or the sensorimotor eye fields and the PSP 50 ERP activity reflects activity in that part of the cortex. Figure 4 shows a scalp potential topographical map for the ERP values at 50 and 300 ms preceding the saccade to the target. The PSP 50 is clearly localized over the frontal scalp area contralateral to the saccade. A second type of topographical mapping is the "spatio-temporal" maps shown in Figure 5. In this case the electrical potential occurring across time are plotted as topographical maps. This type of map shows the ms-by-ms unfolding of the presaccadic ERP activity and its localization. A theoretical analysis of the experimental procedure^[21,81,94] suggests that this is a "planned saccade" and therefore probably involves the frontal eye fields or the sensorimotor eye fields of the cortex. These cortical areas occur in approximately the location of the positive activity. One cannot make an inference about the underlying cortical activity directly from the observed scalp electrical potential without other information. One piece of information is the theoretical analysis, another might be a knowledge of the infant cortex, and a third might come from "brain electrical source analysis" technology (see next section).

Insert Figure 3 about here

Insert Figure 4 about here

Insert Figure 5 about here

Brain electrical source localization. Dipole source localization techniques^[36,37,38,39] will be used for the modeling of neural generators that could generate the obtained scalp voltage surface or CSD topography. Dipole source localization techniques hypothesize electrical dipoles at specific cortical locations. The source dipoles are then used to calculate a hypothetical scalp potential or CSD map based on the characteristics of the dipole, the "forward solution"^[38]. The empirically obtained scalp potential or CSD map is compared against the map based on the hypothesized dipole to determine the fit between the hypothesized and empirical maps. These techniques can be done iteratively with automatic picking of dipole sources (e.g., Brain Electrical Source Analysis (BESA)^[36], Curry and EMSE computer programs from Neuroscan, Inc.). As with the scalp potential or CSD maps, these dipoles may be estimated along several points in time, most likely corresponding to the peaks in the ERP components. These techniques provide a tentative localization of the generators of the ERP pattern. However, they are "post hoc" in nature and subject to empirical indeterminacy because the dipoles that can generate a specific empirical topographical map are infinite^[38]. These techniques require high-density recording^[39]. The feasibility of these techniques in this work can only be assessed after determining the pattern of ERP responding with tradition ANOVA, scalp potential and CSD topographical mapping.

An example of topographical mapping and brain source localization may be found from recent study by the author^[81]. In this study 20-week-old infants were presented with a cue that indicated where a target would occur. The target occurring in the same location as the cue could lead to the infant expecting its occurrence in that location and engaging in a planned saccade to that location^[81,94]. The ERP immediately preceding the occurrence of the saccade, the "presaccadic ERP", is shown in Figure 3. There was a positive presaccadic potential (PSP 50 on figure) occurring about 50 ms before the saccade that occurred primarily over the frontal cortex. It is believed that this saccade planning involves the frontal eye fields or the sensorimotor eye fields and the ERP activity reflects activity in that part of the cortex. The topographical map and the equivalent current dipoles are shown in Figure 6. The top portion of this figure shows the scalp potential topographical map of EEG / ERP activity for this "PSP 50" component. The positive activity occurring over the frontal scalp area is clearly seen as well as negative activity near the midline. This positive-negative combination suggests a current dipole could be located in the cortex. The bottom portion of this figure shows an equivalent current dipole that was found with the EMSE computer program. This dipole was found by analyzing the pattern of scalp activity from the topographical map and hypothesizing a current source with direction and magnitude that would result in electrical current flow to produce such an electrical

potential distribution on the scalp. In this case the dipole was located where the “frontal eye fields” or the “sensorimotor eye fields” would be expected to occur in adults. Thus, the pattern of the presaccadic ERP, the equivalent current dipole analysis, and the theoretical rationale implicating the frontal eye fields in planned saccades in infants^[21,81,94] converge to suggest that this activity represents the involvement of the frontal eye fields in saccade planning in infants.

Insert Figure 6 about here

Selective Attention, Spatial Localization

Many studies of the "endogenous" potentials have shown that psychological manipulations affect ERP latency and amplitude. The ERP component that has been studied the most in relation to psychological behavior is the P3 (P300)^[95,87]. Late-occurring components, such as the contingent-negative-variation (CNV) and N400 also have been often studied. The earliest components (e.g., Pa, Na, P1, N1, and P2), along with the BAER, have been labeled "exogenous" potentials. This labeling originally was applied because these were found to vary in response to physical properties of the stimulus whereas the later-occurring endogenous components may appear only in psychophysiological manipulations. However, these early components are strongly affected by attention, and may be useful in the study of attention effects in young infants. The earliest work to find psychologically-related differences in these components was that of Näätänen^[96,97]. He found that an unusual stimulus presented in a train of auditory stimuli produced a large negativity near the N2 component. This potential, called the "mismatch negativity" (MMN), could also appear as early as the N1 component, and was affected by several psychologically-related manipulations.

The effects of selective spatial attention on early components of the ERP have been shown by Hillyard, Mangun, and their associates. They used a spatial cuing paradigm in which a central cue identified the location of an upcoming stimulus to which a speeded response was to be made. The central cue, such as an arrow, identified the hemifield in which the stimulus was to be presented. The stimulus was presented in that location 75% of the time, and in an unexpected location 25% of the time. Thus, while keeping the eyes on the central location, the subject's best strategy for reducing reaction time to the expected location was to covertly attend to the cued location. They found in many studies^[40,41,60,25] that the amplitudes of the P1 and N1 components over the occipital scalp areas were larger when the target was placed in the attended (validly cued) location than when it was placed elsewhere. In other studies, it has been suggested that attention to foveal stimuli affects the N1 component in the occipital region, whereas attention to peripheral stimuli increases the N1 component to the attended stimuli in the contralateral parietal scalp regions^[61,62,63,64]. Since these early components are thought to reflect sensory and perceptual processes, these findings show the dramatic effect that selective spatial attention may have on such low-level processes. An interesting finding in their series of studies is the potential localization of these processes in extra-striate cortex. These researchers used CSD topographical maps, identification of brain structures with MRI, dipole source modeling, and ingenious experiments over the visual hemi-fields to show this localization^[40,41,25]. For example, using high-density recording only over the occipital and parietal areas, CSD maps seemed to localize the P1/N1 effects outside of the area where the striate cortex would be located. The current flow out of the scalp seemed to come from lateral extrastriate areas rather than striate areas. These suggest that these effects are occurring at later-occurring pathways in the LGN-striate-extrastriate-PG pathway. These studies parallel studies with single-unit recording animal studies that suggest that attention-related effects generally occur in extrastriate areas such as V2, V4, IT, PG, and elsewhere^[98,99,100] (although some recent evidence^[101] suggests that V1 can show selective spatial attention effects under specific conditions).

The enhanced ERP components found as a function of shifting attention to a location in space has been recently shown in young infants^[21]. In that study infants of 14, 20, and 26 weeks of age were tested in a spatial cueing paradigm developed by Hood^[102,103,104]. Covert orienting was assessed with reaction time indices. As found in other studies of young infants^[102,103,104,105,106] infants at all three testing ages showed facilitation of the reaction time to move the eyes from a center location to a cued peripheral location at short SOA's, and inhibition of return to the location at long SOA's. The ERP to the target at cued and uncued locations was examined. The spatial relation between the cue and the target significantly affected the ERP to the onset of the target. There was larger positive ERP component occurring at about 135 ms when the cue and target were in ipsilateral hemifields (valid trials) than when the cue and target were in contralateral hemifields (invalid trials) or when a cue did not precede the target (neutral trials). Figure 7 shows the ERP activity from the onset of the target and shows a clear P1 and N1 component over the occipital scalp leads. Figure 8 shows the ERP from the contralateral occipital lead and scalp potential maps for 14-, 20-, and 26-week-old infants. The validity effect on this positive ERP component did not occur (or was very small) in the 14-week-old infants, occurred at larger levels in the 20-week-old infants, and was at its largest in the 26-week-old infants. This change is illustrated in the scalp potential maps in the bottom portion of Figure 8, which shows a change over the three ages in the localization and amplitude of this activity. The ERP component occurred in the contralateral occipital leads for the target onset (peripheral visual field; Figure 7, Figure 8). This ERP component was similar to the P1 (i.e., P100, or first positive ERP component) found in adult ERP recordings^[25,26]. A negative ERP component occurred around 260 ms following the onset of the target that was larger in the contralateral posterior leads and was larger on the cued trials relative to the neutral trial. This ERP component was similar in form to the N1 component found in adult participants, although in adults this component generally occurs around 175 ms following stimulus onset (e.g., 150 to 200 ms in adults^[49,50]). The enhanced P1 on the valid trials was similar to that found in spatial cueing procedures using adult participants^[107,108,109,110]. This early ERP component reflects sensory and perceptual processes and suggests that covert orienting of attention affects the early stages of processing rather than later stages^[111,107,60,25]. The existence of this component in the older age infants was a "covert" assessment that covert orienting had occurred

in response to the peripheral stimulus when it was presented as a cue. The results from this study indicated that infants were shifting attention to the cued location covertly and that this early sensory-perceptual gating occurs in infant attention as it does in adult attention.

Insert Figure 7 about here

Insert Figure 8 about here

Presaccadic and Saccadic ERP's

Saccadic eye movements to localize stimuli have several brain systems involved in their control. Schiller^[112,113], for example, has summarized neuroscience work on the primate visual system and eye movement control. Several systems control eye movement, including smooth pursuit, reflex saccades, and target saccades. Different pathways control these eye movement systems (e.g., magno- vs parvo-cellular^[114,115,116,117,118,119]). Different areas of the brain control these eye movement systems. For example, the medial temporal and medial superior temporal cortex initiates smooth pursuit, and the cerebellum maintains it. A system composed of the lateral geniculate nucleus, primary visual area, suprasylvian cortex, and superior colliculus controls reflexive saccades. A brain pathway affected by attention controls attention-directed targeted saccades, and involves the lateral geniculate nucleus, visual areas 1 and 2, parietal cortex area PG, and frontal eye fields^[116,117,118,119,120]. Frontal eye fields then control the superior colliculus to control eye movements, or directly control motoneurons (e.g., oculomotor nerve) to effect eye movement. Attention may operate in a nonselective manner on visual areas, including enhancing form and color discrimination, motion detection and visual tracking, and eye movements. The mesencephalic reticular formation and the limbic system^[121,122], as well as dopaminergic and cholinergic^[123] control this "arousal" form of attention. This arousal/sustained alertness system sustains attention and maintains an alert, vigilant state. This system subserves several component systems, including audition, visual-spatial attention, and form/color object discrimination^[124,125]. Attention may also operate in a selective manner. Selective attention enhances responses to specific objects or categories for form or color discrimination in the inferior temporal cortex^[126]. Attention may also selectively enhance areas in the "posterior attention system"^[127,128,124,125,129] for targeted saccades controlled by the frontal eye fields. The parietal attention system and the frontal eye fields selectively inhibit reflexive saccades controlled by the superior colliculus.

Many studies have shown the involvement of the frontal eye fields in "voluntary" eye movements. For examples, when monkeys are trained to make a saccadic eye movement from a fixation point to a stimulus (or location) in the peripheral, there is activity in several parts of the frontal eye fields that precedes the eye movements^[130,131,132,133,134]. Lesion^[135,136] and stimulation^[136] studies of the frontal eye fields and superior colliculus show that each can sustained targeted eye movements. However, the frontal eye fields seem uninvolved in reflex saccades to unexpected peripheral stimuli, or very short-latency express saccades.

Whereas single-unit recording of cortical activity is not feasible in human studies, EEG recording of presaccadic cortical potentials has shown cortical activity preceding saccadic eye movement. Three types of EEG potential activity have been found preceding saccade onset. First an early negativity is observed that starts up to 1 s prior to saccade onset and has a maximum negativity over the vertex^[65,66,67,68]. This negativity is thought to reflect either the activation of the frontal eye fields prior to saccade onset, or alternatively, may reflect activity in the supplementary eye fields of the supplementary motor area. Second, a positivity occurs about 30-300 ms prior to saccade onset can sometimes be identified^[65,66,67,68]. Finally, just prior to saccade onset, there is a positive "spike potential" in the EEG recording^[65,66,67,69,70]. [Brickett#Weinberg#Davis]. The spike potential is largest over the parietal scalp leads (e.g., P3 and P4), and is larger contralateral to the eye movement.

An interesting aspect of the presaccadic negativity is its relation to voluntary eye movements. This negativity is larger to self-paced saccades than to visually-triggered saccades or to unexpected than expected peripheral stimuli^[67,71,72]. One study of the presaccadic negativity separated saccades into regular visually triggered saccades to an unexpected stimulus, saccades to a predicted target location, and saccades back towards the predicted location of a previous fixation point^[73]. The anticipatory saccades toward the predicted target location and the saccades back towards the previously fixated target site showed an early widespread negativity over the contralateral cortex and a negativity over the contralateral central lead (e.g., C3 or C4). The earliest widespread negativity was interpreted as reflecting response preparation, whereas the central contralateral negativity was interpreted as reflecting neural activity in the frontal eye field or premotor cortex. Finally, visually triggered saccades showed only a contralateral parietal activity fairly closely to the saccade onset (30 ms). The presaccadic spike potential, occurring over the parietal cortex, also seems to occur most frequently in voluntary rather than reflexive eye movements^[70].

Infant Saccade Planning

The use of presaccadic ERP to investigate the cortical areas involved in infant saccade planning has recently become of interest to several investigators. Two studies examined presaccadic ERPs in adults and infant^[137,76]. The study presented infants with a focal stimulus followed by a peripheral stimulus presented simultaneously with the focal stimulus ("overlap" condition) or after a brief delay ("gap" condition). Adults in this paradigm showed the presaccadic slow wave activity and spike potential for both conditions^[137]. However, they found no evidence of these specific presaccadic ERP components for 6-month-old infants tested in a similar manner^[76]. They concluded that saccades toward the peripheral targets for infant participants in their study were under subcortical control (e.g., superior colliculus) and did not involve cortical saccade planning. However, the procedure in these studies involved exogenous

orienting to a cue in an unexpected location. The infants in this procedure may have not developed an expectation about the location of the target since there was no previous cue to indicate where it would occur. Thus, "planned" saccades may not have been appropriate for the infants.

Two recent studies reported in a thematic collection of the *Infancy* journal organized by the author^[94] used the "visual expectation procedure" to study presaccadic ERP changes and saccade planning in infants^[78,138]. The visual expectation procedure presents stimuli in locations in a regular sequence. For example, a pattern may occur alternately on the right and left sides, or in a sequence such as right-right-left. Infants will make anticipatory saccadic eye movements toward the upcoming stimulus location before the stimulus is presented. They also will respond more quickly to a predictable location than to an unpredictable one. This implies that an expectation has developed about the upcoming stimulus and suggests that the saccades occurring toward the expected location are planned rather than reflexive, and therefore should involve cortical areas involved in voluntary saccades.

A recent study by the author^[21], and a special thematic collection in the *Infancy* journal^[94,81,78,138] have examined the ERP indices of saccade planning. The author examined presaccadic ERP changes in young infants^[21]. The infants ranged in age from 3 to 6 months and were tested in a spatial cueing paradigm^[102,103,104]. The ERP occurring immediately before the saccade to the target was recorded and analyzed. Figure 3 shows a positive presaccadic potential (PSP 50 on the figure) that occurred about 50 ms before the saccade to the target in an expected location and occurred over the frontal scalp areas. This occurred only for the trials in which the cue predicted the location of the target. For trials on which there was an eye movement toward the cue whether or not there was a target, there was also a positive presaccadic potential that occurred about 300 ms before the saccade toward the cued location^[81]. Figure 9 shows the ERP for electrodes around the PSP 50 and around the PSP 300. There was an interesting developmental change in the size of this presaccadic activity. Figure 10 shows scalp potential topographical maps for this PSP 50 for 14-, 20-, and 26-week-old infants. This presaccadic activity did not occur in 3-month-old infants, was stronger in 4.5-month-old infants, and largest and more widespread in 6-month-old infants. This suggests that there is a developmental change over this age range in the amplitude of the ERP response and in the corresponding frontal areas controlling this activity. Figure 6 shows the potential map and the result of an equivalent current dipole analysis for this activity. The dipole was located in the area of the cortex that in adults has the frontal eye fields. The location of this scalp activity over the frontal areas contralateral to the saccade was interpreted as consistent with activity in the FEF or sensorimotor eye fields controlling eye movements to a predicted target.

Insert Figure 9 about here

Insert Figure 10 about here

Infant Recognition Memory and ERP

The study of endogenous potentials in infant cognitive psychophysiology has had two influences. First, the P3 (P300; P3a; P3b) is an ERP component that is known to be related in adults to several psychological processes. It is generally evoked in the "oddball" paradigm, that consists of one stimulus set being presented frequently (e.g., 80%) and another infrequently (20%). The P3 is an ERP component of positive electrical potential, occurs at around 300 msec after the stimulus presentation, occurs primarily over the parietal scalp region, and occurs with greater magnitude to the to the infrequently presented stimulus. Second, investigations by Courchesne^[139,140] with young children older than 2 years has identified two ERP components occurring primarily in children. The Nc is a negative ERP component, has a latency between 400 to 1000 msec, is distributed over the frontal and central scalp regions, and is thought to be a sign of enhanced attention to surprising, interesting, or psychologically significant, visual or auditory stimuli. The Pc is a positive ERP component, has a latency longer than 1000 msec, has a similar scalp distribution as Nc, and occurs to interesting visual or auditory stimuli.

The first publications studying endogenous ERP components in young infants in experimental settings came in 1981. One of those was a study of ERP during the oddball paradigm by Courchesne, Ganz, and Norcia^[57]. Courchesne et al. reported data from 10 infants who ranged in age from 4 to 7 months. The infants were presented with slides of two women for 100 msec. One slide was presented on 88% of the trials, and the other on 12%. The frequent face should become familiar to the infant over the course of stimulus presentation, whereas the infrequent should be a discrepant or novel stimulus (e.g., the "oddball" stimulus). Research with older children and adults showed that the endogenous component P3 occurs over the parietal region, whereas the Nc and Pc components occur over the frontal region^[139,140]. In the Courchesne et al.^[57] study, EEG was recorded over the frontal and parietal regions. By recording at these sites, they could determine if these endogenous potentials existed in young infants, and distinguish them by scalp location and relation to the frequent/infrequent events.

The Courchesne et al.^[57] study had two main findings. First, a significant negativity occurred in the ERP in all 10 infants over the frontal region, with a latency of about 500-700 msec. Because of its latency and scalp distribution, it was concluded this was a Nc component^[139,140]. This negative ERP occurred for both the familiar and novel face, but was largest for the infrequently presented face. Figure 11 (bottom tracing) shows the tracing from the ERP to the frequent and infrequent face. The difference between the two types of stimuli is highlighted by the crosshatching on the recordings occurring at the FZ (frontal) site. Second, a late positive component in the ERP occurred, primarily over the frontal electrode sites (Figure 11). This component had a latency and distribution like that found with older children for a Pc component. This infant Pc component was not different in amplitude for the familiar and novel faces. No

evidence was found for a positive ERP component near 300 msec over the parietal region, i.e., the P3 component found in research with older children and adults.

Insert Figure 11 about here

The finding of late ERP components in 4 to 7 month olds that were related to the frequent/infrequent manipulation was extended to younger and older infants by Karrer and Ackles^[54]. Karrer and Ackles used infants at ages 6 weeks, 6 months, 12 months, and 18 months. They used a frequent/infrequent presentation of stimuli similar to Courchesne et al.^[57], with checks and random stimuli for the youngest group, faces for the 6 month olds, and pictures of stuffed animals and toys for the older infants. They recorded the ERP from frontal, central, parietal, and occipital sites. Their results were similar to those of Courchesne et al.^[57]. There was a large negative ERP component around 600 msec following stimulus presentation. For the three oldest groups, at the central scalp region, the amplitude of this component was larger for the infrequent than for the frequent stimulus. There was a significant Nc response at the frontal recording location that was not differentially affected by the oddball presentation. No large negativity was found at the parietal or occipital sites. The Nc component at both the frontal and central scalp locations increased in magnitude over the age range of 6 to 18 months. Studies by Kurtzberg and associates^[141] with speech sounds ("da" and "ta") presented frequently/infrequently extended the finding of a Nc component to auditory stimuli.

These studies have two findings. First, significant ERP changes are found in conjunction with the frequent/infrequent presentation of stimuli. This indicates recognition by the infant of the relative novelty/familiarity, or probability of the stimuli. As such, it shows a recognition memory for the stimulus, and an increased attention level to the novel stimulus. This parallels what has been found in adults with the P3 ERP component. It complements the finding that infants at this age in visual preference paradigms spend more time looking at a novel than at a familiar stimulus. The possibility that there are developmental changes in these components^[54,55] indicates the possibility of assessing developmental changes in recognition memory.

The second finding in these studies is the absence of a ERP component that could be related to the P3 found in adults. The components that were found in these studies with infants were at different scalp sites (frontal, central, rather than parietal) and at different latencies (700 msec, 1300 msec, rather 300 msec) than the P3 component. The frequent/infrequent presentation style was an analog to the "oddball" paradigm used with adults, and had similar effects in all of the cited studies on the Nc component, but no P3 component was found. It has been argued that the exogenous ERP's in infants, reflecting sensory processing, occur at 200 to 300 msec, so that a P3 sensitive to psychological variables might be physically impossible^[8]. It has been concluded by Courchesne^[4,142] that the P3 does not exist in infants, and emerges as a distinct ERP component late in the second year.

A different set of research findings has reported a probability effect with positive waves in the ERP around 300-600 msec. The first of these, published in the same year as the Courchesne et al.^[57] study, was done by Hoffman, Salapatek, and Kuskowski^[143]. They presented 3-month-old infants with high-contrast square wave gratings for 500 msec for several trials. Their procedure differed from the studies cited earlier in that they had a "familiarization phase" that consisted of a single stimulus presented for 40 trials. Then, in a "test phase", the familiar stimulus was presented for 80% of the time (frequent-familiar) and a new stimulus was presented for 20% of the time (infrequent-novel). They recorded scalp potentials at occipital and parietal (Study 1), and frontal (Study 2) locations, during the stimulus. A positive ERP component in the occipital scalp leads was found around 300-400 msec following stimulus presentation. This ERP component was larger to the infrequent-novel stimulus ERP in the test phase compared to the ERP during the familiarization phase. They did not find a difference between the frequent-familiar and infrequent-novel stimuli presented in the test phase. Nelson and Salapatek^[58], using a similar test protocol but employing longer recording intervals, found a negative ERP component at the central leads between 500 to 700 msec distinguishing the familiar phase ERP from the test phase infrequent-novel stimulus. A positive component was found at central and frontal leads at longer intervals (900 msec), that distinguished between the frequent-familiar and infrequent-novel stimuli on the test trials.

The studies of Courchesne et al.^[57] and Karrer and Ackles^[54,56] reported the later components (Nc and Pc), whereas the Hoffman et al.^[143] and the Nelson and Salapatek^[58] studies reported earlier positive ERP components. There were several differences between these studies that might account for the different results. A major difference is the use of a familiarization phase in the latter studies, and the lack of such a phase in the former ones. The use of a familiarization phase is probably important in this research. In the studies without the familiarization phase, it is likely that a memory for the frequently presented stimulus is gradually building up over the course of the presentations, whereas the infrequently presented stimulus retains its relative novelty. A possible confound with each of these studies is that the "infrequent" stimulus is also the "novel" stimulus. Thus, it may not be the "novelty" of the stimulus that elicits the ERP differences, but the mere "frequency".

A study by Nelson and Collins^[51] addressed these problems. They recorded EEG over several scalp locations in 6-month-old infants, with long enough recording intervals to detect the Nc and Pc components. A familiarization phase consisted of presenting two face stimuli with equal probability to the infants on multiple trials. The test phase had three types of presentations: a familiar stimulus presented frequently (60% ; frequent-familiar), a stimulus from the familiarization period but presented infrequently in the test phase (20%; infrequent-familiar), and a stimulus never presented, and presented infrequently (20%; infrequent-novel). This study was unique in that the infrequent-novel stimulus was a different face on each trial, thus prohibiting any familiarization to the novelty of the face. This study could compare the relative probability of the stimulus separate from its novelty (frequent-familiar compared with

infrequent-familiar), and novelty of the stimulus separate from its relative probability (infrequent-familiar compared with infrequent-novel).

The most important results from this study were ERP differences found in the central scalp locations (Figure 12). First, there were no differences before 750 msec or after 1400 msec in the three conditions. Second, at the central lead between 750 and 1400 msec, there was an increased positivity in the test-phase ERP to the infrequent-familiar stimulus relative to the frequent-familiar (or to the familiar stimuli during the familiarization phase). Thus, though the infrequent-familiar should be recognizable to the infant, its relative probability alone (a frequency effect) was sufficient for infants to distinguish it from the frequently presented familiar stimulus. There was also a "novelty" effect. The ERP to the frequent-familiar stimulus was positive at this latency, whereas the ERP to the infrequent-novel stimulus was negative. The ERP to the infrequent-novel stimulus was similar to the Nc component found in the previous studies. Thus, in these "oddball" paradigms, modified from adult versions, infants are responsive both to stimulus novelty and to the frequency of stimulus occurrence. Nelson and his colleagues have used this technique in several recent studies to examine recognition memory and frequency effects in infants^[6,52,53,144]. An important developmental finding from some of those studies is that at 4 months of age there is no difference between the ERPs to the three conditions, whereas by 6 months^[51] or 8 or 12 months^[52,53].

Insert Figure 12 about here

The studies cited thus far indicated that very late components (e.g., greater than 700 msec) of the ERP distinguish the "oddball" stimulus from the familiar stimulus, whereas earlier components (e.g., around 300 msec) do not. One relatively recent study with 5 to 10 month old infants reported a ERP component that was very similar in duration and topography to the adult P3^[86]. That study used the presentation of tones (1000 or 2000 Hz), with a fixed presentation of 10 auditory stimuli, with the "oddball" or "target" stimulus occurring in the 7th, 8th, 9th, or 10th position in each 10-tone sequence. They found an enhanced positive component of the ERP around 600 msec in the infants to the target (infrequent-novel) tone. Adults tested in the same study showed positive ERP component that was much larger, had a larger frequent/infrequent difference, and had latencies around 300 msec. The largest ERP differences for both infants and adults were in the central and parietal recording locations. This finding of a P3-like component in the infant ERP is different from that found with infant subjects for visual stimuli or for previous studies with auditory stimuli^[141]. This finding needs to be replicated with testing protocols similar to those used in past research^[57,51] in order to compare it with the previous studies. It is promising in the selection of a test protocol that elicits a significant ERP component with scalp topography similar to that found with adults.

(the next paragraphs are taken from Richards, 2000)

I have just completed a study using this procedure, measuring ERPs, and presenting the FF, IF, and IN stimuli in different phases of attention^[80]. As with the other studies of infant recognition memory^[145,146] the infant's attention is elicited with a "Sesame Street" move, "Follow that Bird", that elicit 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 13 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 13 show the ERP changes for the three presentation procedures (FF, IF, & 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 to 1500 ms) show 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 13).

Figure 14 shows topographical maps of the Nc and 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.

Insert Figure 13 about here

Insert Figure 14 about here

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 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^[147] and for the individual cognitive processes occurring for transient responses to the stimulus^[80].

Implications for Abnormal Development

There is a long history of using EEG and ERP in the study of abnormal infant development. Almost all of the work in this area with infants has been with spontaneous EEG or with the exogenous ERP components. The work with exogenous ERP components of abnormal infants has focused on Down's Syndrome infants, infants and children with autism, preterm infants, infants with respiratory difficulties at birth, infants with developmental delays, and infants with hearing and visual problems^[142,148,7,27]. The endogenous ERP components and ERP components during complex cognitive processes have not been extensively investigated in abnormal infant development. The studies with the endogenous ERP components of interest to infant cognitive psychophysiology for the assessment or diagnosis of abnormal children have evaluated older children^[142].

The study of abnormal development with endogenous ERP's would be useful. It is usually assumed that prenatal and perinatal risk factors, particularly medical risk factors, have their effects on cognitive or intellectual functioning carried through childhood by changing CNS systems responsible for information processing. These structures may prohibit appropriate interaction with the environment in infancy, retarding appropriate developmental changes throughout early childhood, leading to poor cognitive performance in the early school years. Although with exogenous or sensory ERP's some of these affected areas can be identified in infants, it is not basic sensory processes for which the risk exists--it is higher cognitive functioning. Thus, the psychophysiological tasks that evaluate cognitive activity related to physiological systems would be inherently more useful in identifying abnormal cognitive behavior in infants that should be related to abnormal cognitive outcome in childhood. The ERP / recognition memory relation might be one of those useful for identifying infants at risk for later poor intellectual function. Some behavioral tests of infant recognition memory are one of the best predictors in young infants of normal intellectual outcome at 5 years of age^[149,150]. This prediction may be aided by examining indicators of the underlying physiological abnormality, if any, with ERP recording.

There is at least one example of the use of endogenous ERP with infants having developmental abnormalities. Karrer and Ackles^[55] recorded Nc in Down's Syndrome infants at ages 6 months through 2 years and found the physical characteristics (latency, amplitude, duration) of this endogenous ERP component to be similar in the Down's Syndrome infants and normal infants. The normal infants showed larger Nc amplitudes to the "oddball" stimuli than to repeated stimuli, whereas the Down's Syndrome infants showed the same Nc amplitude to both novel and repeated stimuli (Figure 15). The Down's Syndrome infant was thus responding to the stimulus, but did not discriminate the novel properties or show recognition memory. Older children with Down's Syndrome show abnormal endogenous potentials associated with cognitive processing^[151,142].

Insert Figure 15 about here

Figure Captions

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

Figure 2. Scalp recording sites, with multi-channel high-density recording.

Figure 3. The ERP responses occurring immediately prior to the onset of a saccade to the cued location. The responses are presented separately for the 40 recording electrodes, and separately for the cued-exogenous, uncued-exogenous, and endogenous saccades. The data in this figure were plotted as if the infant were making a saccade toward the left side. Taken from Richards, 2001^[81].

Figure 4. Topographical scalp potential maps for the PSP 50 and PSP 300 components for the difference between the cued-exogenous and the combined endogenous and cued-exogenous saccades (left figure), and for the difference between the combined cued-exogenous and endogenous, and the cued-exogenous saccades (right figures). The maps were plotted as if the infant were making a saccade toward the left side.

Figure 5. Topographical scalp potential maps for the presaccadic ERP responses for the cued-exogenous saccades and the combined endogenous and uncued-exogenous saccades. The maps are shown as a series and represent 16 ms averages of ERP from 94 ms preceding the saccade onset through 14 ms preceding saccade onset. The PSP 50 is apparent in the frontal locations contralateral to the cued-exogenous saccades (top figures) beginning at -46 and -30 ms and declining by -14 ms.

Figure 6. The scalp potential topographical map representing the electrical potential occurring for the presaccadic positive component around 50 ms before saccade to an expected target (Figure 3) and an equivalent current dipole representing a hypothesized current source for this scalp electrical potential distribution.

Figure 7. The ERP responses to the peripheral stimulus onset when it was presented as a target. The responses are presented separately for the 20 recording electrodes, and for the trials on which the cue and target were on the same side ("Valid"), different side ("Invalid"), or when no cue occurred but the target was presented ("No-Cue Control"). The data is presented as differences from the ERP on trials in which a peripheral stimulus was not presented as a target. The data for the electrode locations were reversed to the opposite hemisphere for the trials on which the peripheral stimulus was presented on the right side, so that the even numbered electrodes represent recording sites contralateral to the stimulus and odd numbered electrodes represent recording sites ipsilateral to the stimulus. The approximate location of the P1 and N1 components are identified for the O₂ electrode. The median number of trials for each electrode going into the grand average were 126, 135, and 129 for the valid, invalid, and no-cue control trials.

Figure 8. Top figures: The ERP responses on the contralateral occipital electrode to the peripheral stimulus onset when it was presented as a target. The responses are presented separately for the three testing ages, and separately for the valid (solid line), invalid (small dashes), and no-cue control (long dashes) trials. The data is presented as the difference from the ERP on the no-stimulus control trial. The approximate location of the P1 and N1 components are identified on each figure. Bottom figures: Topographical scalp potential maps for the P1 effect for the three testing ages. These maps plot the difference between the valid and no-cue control trials for the peak potential occurring between 50 and 200 ms following peripheral stimulus onset, which on the average occurred about 135 ms following peripheral stimulus onset.

Figure 9. The ERP responses for four of the electrode locations shown in Figure 3. The presaccadic ERP for F₄ and FC₆ show a large presaccadic positive ERP component that occurred about 50 ms before saccade onset for cued-exogenous saccades (PSP 50). The presaccadic ERP for P₄ and PO₆ show a large presaccadic positive ERP component that occurred about 300 ms before saccade onset for the cued-exogenous and endogenous saccades (PSP 300).

Figure 10. Topographical scalp potential maps for the PSP effect occurring in the valid trials, separately for the three testing ages. These maps plot the peak potential for 12 ms centered at 44 ms before the onset of the saccade toward the peripheral stimulus.

Figure 11. Event-related potentials from electrodes near the eye (LoE and UpE) and scalp electrodes on the frontal scalp location (FZ) to frequent (thin lines) and infrequent (thick lines) faces from five infants ranging in age from 4 to 7 months. The crosshatching represents the difference between the two stimuli types. From Courchesne et al., 1981.

Figure 12. Event-related potentials for the test phase in a recognition memory study. These come from the occipital, parietal, central, and frontal scalp recording locations (OZ, PZ, CZ, FZ). The data are from the frequent-familiar (dashed line), infrequent-familiar (thick solid line) and infrequent-novel (thin solid line). Significant differences between conditions occurred at CZ. From Nelson & Collins, 1991.

Figure 13. The ERP in response to the frequent familiar, infrequent familiar and infrequent novel presentations for 6-month-old infants. These recordings are from the Fz (frontal 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.

Figure 14. A topographical mapping of the ERP components occurring during sustained attention. The ERP components were the Nc (400 to 700 ms; top figures) and the later slow wave component (700 to 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 represents 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 is 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.

Figure 15. Event-related potentials to normal and Down's Syndrome infants from 6 weeks through 2 years of age, shown for the frontal and central scalp recording locations (FZ,CZ). The data are from frequently presented stimuli (thin lines) and infrequently presented stimuli (thick lines). The FZ/CZ recordings on the left are from normal infants, and show larger Nc responses to the infrequent stimuli in the CZ lead beginning at 6 months of age. The recordings on the right are from the Down's Syndrome infants, and show slightly larger Nc responses to the frequent rather than the infrequent stimuli, or show no difference between the frequent and infrequent stimuli. From Karrer & Ackles, 1988.

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