Infant brains detect arithmetic errors

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Contributed by Michael I. Posner, June 29, 2006

A current debate is whether increased looking time in infancy is related to violation of expectations. In this study, 6- to 9-month-old infants' brain activity was analyzed during presentation of correct and incorrect solutions to simple arithmetic equations [(e.g., presentation of $1 + 1$; one doll on a TV monitor, with another doll added from behind a screen, followed by a solution of 2 (correct) or 1 (incorrect)]. Infants looked longer at incorrect solutions than at correct ones. Event-related potentials, time-locked to the presentation of the solution, also differed between conditions, with greater negative activity for the incorrect solution condition. Spectral analysis showed a similar pattern to that of adults observing correct and incorrect arithmetical equations. These findings show (i) that the brain network involved in error detection can be identified in infancy and (ii) that this network can support an association between looking time and violation of expectations.

early arithmetic | event-related potential | error detection | executive attention | self-regulation

Wynn (1) showed that 5-month-old infants could discriminate between correct answers (e.g., $1 + 1 = 2$) and errors in simple arithmetic problems (e.g., $1 + 1 = 1$). When the number of dolls in a case did not agree with the number seen being placed in the case, babies looked longer than when the number agreed (see also refs. 2, 3). Wynn concluded that the infants were able to perform simple arithmetic calculations based on the assumption that infants look longer at unexpected events (4–6).

Some have argued that infants' looking time, instead of being a sign of their understanding of basic arithmetical procedures, reflects their tendency to look longer at displays that differ perceptually from what has already been seen (7, 8). The issue raised by Cohen and Marks (7) and Haith and Benson (8) affects our conclusions not only about infants' understanding of numbers but also about their understanding of the physical, biological, and social world. Experiments in these fields rest heavily on the assumption that looking time indicates infant error detection and violation of expectations. How can we be sure that this interpretation is correct? How early in life can error detection be shown?

Error detection and the resolution of conflict are considered signs of the development of an executive attention network that involves the anterior cingulate and other frontal brain areas (9). In conflict tasks, children must override a prepotent response, substituting a conflicting response (10, 11). The earliest behavioral signs of executive attention as measured in the efficiency of conflict resolution have been found by the end of the first year of life (12). Later, between 2 and 4 years of age, there appears to be a dramatic increase in the efficiency of children's conflict resolution. For error monitoring, the earliest signs have been observed so far at 39–41 months of age, in the form of increased reaction time after an error (13).

In adults, brain activity related to error detection has been studied extensively (for example, refs. 14–18). These studies report activity with negative polarity over middle-frontal areas when an error was detected. Source localization and functional MRI studies have identified the anterior cingulate cortex as the possible source of this activity (17, 19–22). This error negativity

is obtained not only in cases of self-made errors but also when perceiving erroneous information (23, 1).

There is currently a lack of connection between the “looking time at impossible events” effect and what is known regarding the development of brain mechanisms mediating error detection. We therefore designed a study combining Wynn's paradigm with the electroencephalogram (EEG)/event-related potential (ERP) methodology. Our aim was to look at infants' brain activity during presentation of correct and incorrect simple “puppet” arithmetical equations, looking for evidence error detection under the incorrect condition. Infant brain activity was also compared with that of adults presented with correct and incorrect real arithmetical equations.¹ Our methodology took into account the criticisms and limitations of Wynn's original paradigm, pointed out by Wakeley *et al.* (24, 25). Both behavioral looking times and brain waves were measured in parallel, by using the strictly structured and timed conditions necessary for the ERP methodology (see Fig. 1).

Results

Behavioral Results. Looking-time coding was done offline based on the digital videotapes for each session. Inter-rater reliability was calculated based on the coding of 20% of the participants (five infants). Percent agreement regarding whether the trial was codable or uncodable was 98.8%. Percent agreement on looking time (millisecond accuracy) was 92%. The Pearson correlation between looking times as coded by two raters was $r = 0.99$.

Behavioral looking-time results were consistent with the hypothesis, replicating Wynn's original 1992 finding (1) in showing that the mean looking time for the correct solution (i.e., $1 + 1 = 2$) was shorter than for the incorrect solution condition (i.e., $1 + 1 = 1$). Mean looking time was 6.94 s (SD, 4.37) for the correct solution condition and 8.04 s (SD, 4.66) for the incorrect solution condition. The difference between looking times for correct vs. incorrect conditions was significant in a one-tailed t test, $t_{(24)} = 2.0436$, $P = 0.025$. Of the 24 participants, 15 also showed a difference between the two conditions in this direction. No significant differences were found in age or sex between infants who showed the behavioral effect and those who did not.

EEG/ERP Results. All analyses were based on a group of nine channels located above the middle-central area, between and including electrodes Cz and Fz of the 10–20 system (see oval outline in Fig. 2). This localization is comparable with the classic location of the error-related negativity in the literature (15, 16,

Conflict of interest statement: A.B., G.T., and M.I.P. declare that they have no competing financial interests.

Abbreviations: EEG, electroencephalogram; ERP, event-related potential.

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¹Tzur, G. & Berger, A. Cognitive Neuroscience Society Annual Meeting, April 10–12, 2005, New York, NY, abstr. C54.

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Fig. 1. Stimuli were modeled after those used by Wynn (1). The puppet versions of the different mathematical equations ($1 + 1 = 1$, $1 + 1 = 2$, $2 - 1 = 1$, and $2 - 1 = 2$) were videotaped and displayed on a 21-inch flat-screen TV. (Upper) Stimulus phases from the infants' point of view. (Lower) Stimulus phases from the video-camera point of view, facing the infants' faces for looking-time calculations, with the mirror behind the child indicating the stimuli being displayed.

21, 26, 27). As can be seen in Fig. 2, the localization of the effect was remarkably similar in the infants and the adults.

Analysis of electrophysiological activity was conducted only for those infants who showed the behavioral effect (15 infants).^{||} The time window for analysis was defined as 330–530 ms after stimulus presentation, according to the preliminary difference-wave analysis of the grand-average pattern (see Fig. 3). The mean amplitude for the channel group was extracted for each infant in each condition. Data were analyzed by using repeated-measures ANOVAs for the time window, with trial-type condition (correct and incorrect solution) as the within-subjects variable. Analyses revealed significantly greater negativity for the incorrect condition compared with the correct one. The mean amplitude for the correct solution condition was $9.88 \mu\text{V}$ (SD, 6.67), and the mean amplitude was for the incorrect solution condition was $-14.78 \mu\text{V}$ (SD, 9.81; $F_{(1,14)} = 8.4$; $P = 0.012$; mean of square error = 733.5).

Time-Frequency Analysis. A wavelet analysis was conducted to find the relative frequency band in which the “error detection” effect was obtained for infants vs. the adult data. As can be seen in Fig. 4, the spectrogram from the Fcz electrode for 15 infants in the correct and incorrect conditions (left column) was found to be

remarkably similar to the pattern previously found with adults (right column) and the corresponding ERP waves. In both groups, the relative power increase in the incorrect condition can be seen mainly in the θ - and α -frequency bands. Note that the timing of this “burst,” which is clearly evident in the relative power increase for the incorrect condition, is parallel to the significant difference found in the ERP amplitudes. This consistency between the burst in the time-frequency and ERP analyses also was true for the adult data.[¶] The power increase in the incorrect condition was significant in the adult data in both the α and θ ranges. Although in exactly the same direction, because of the fact that the wavelet analysis was based only on a very small amount of trials with the infants, these differences only reached marginal significance in the infant data.

Discussion

Behavioral data in this study replicated the findings of Wynn (1), with infants looking longer at the incorrect solutions. In addition, infants' brain activity indicated that there was detection of the “error” in the arithmetic information presented to them. The topography and frequency (θ -band effects) of this activity were quite similar to what has been found in adults. However, it should be noted that there is a difference in the order of magnitude between the effects found in infants and those found in adults that can be seen in the scales presented in Figs. 2 and 4. The time course of the effects indicated that the error detection was somewhat later in the infants compared with the adults, which may reflect their general slower processing.

Because effects are found in frontal structures known to be important in dealing with error, violations of expectation and conflict between competing cognitions have been interpreted as involving high-level monitoring of conflict or performance (28). The presence in 7-month-old infants of the same brain response as adults suggests that the onset of executive control can be found in infancy. Although at 7 months, infants are not yet able to regulate their own behavior when detecting their own errors, and although it will take some years until they can show a more

^{||}The electrophysiological data of those infants who did not show the behavioral effect showed a pattern of differences in the relative frequency bands' power that was similar to, although weaker than, that found in infants who showed the effect. This fact, together with the lack of differences in any additional background variable (age and sex), suggests no real differences between those infants showing the effect and those not showing it (but does suggest likely transitional differences in infants' engagement with the stimuli in the laboratory situation). Infants who were less engaged may have shown noisier and less-consistent behavior during the trials, making it more difficult to extract a consistently significant pattern. In some of the trials, they may not have detected the incorrectness of the equation, in others they may have detected it relatively later, and in others they may have detected it as well as the infants who showed the behavioral effect. The sample size of this study was moderate and did not allow for further exploration of individual differences. The study of such differences requires further research that could lead to important early markers of individual differences in executive attention and in arithmetical understanding.

Fig. 4. Time frequency analysis results. (Top and Middle) Grand-averaged time–frequency plots from the Fcz electrode. Dark areas indicate low-power values, and light areas indicate high-power values. (Left) Data from infants. (Right) Data from adults. (Top) Relative powers of brain activity after the presentation of a correct solution. (Middle) Relative powers of brain activity after the presentation of an incorrect solution. Note the relative increases in the power of δ -, θ -, and lower α -frequency bands for the incorrect condition compared with the correct one. (Bottom) Corresponding ERP wave graphs. The time window is shown in gray.

to the presentation of the solution. Only trials that passed the behavioral criteria were included in the analysis. The segmented data were inspected for artifacts (e.g., bad channel, eye movement) while excluding channels within each segment that exceeded the fast average amplitude of 200 μ V or the differential average amplitude of 100 μ V. Segments having >10 bad channels were excluded. Segments with <10 bad channels were included while replacing the bad-channel data with spherical interpolation of the neighboring channel values. Fortunately, not many trials were lost in this cleaning process, because the characteristic behavior of the infants was (i) being fully captivated by the video stimuli, (ii) watching attentively without moving (and mostly without even blinking), or (iii) not being interested in the video at all. The trials in which the infant did not look at the video (even partly) but that did include movement

of the eyes and head were screened out even before the EEG analysis by the behavioral criteria that we used, which strictly required that the infant look at the screen during all phases of the trial. An average of 5.4 clean segments per infant in each condition were entered (minimum, 3; maximum, 9).

Before averaging, each trial was re-referenced to the average of all of the sensors at each time point. Finally, after averaging the trials for correct and incorrect conditions, subsets were baseline-corrected to 100-ms presolution presentation.

Analysis was strictly guided by hypothesis. It was conducted on a group of nine channels located above the middle–central area, between and including electrodes Cz and Fz of the 10–20 system (see Fig. 2), because this localization is comparable with the classic location of the error-related negativity in the literature (15, 21, 26, 27) and the adult data. We looked for a difference

between conditions, expecting that for the incorrect solution, the amplitudes would be of negative voltage.

Time–frequency analysis of the data was conducted by using wavelet-based analysis (35), testing for relative changes in the power of different frequency bands through time. The wavelet analysis was based on each participant's unfiltered EEG data after it was segmented, time-locked to the presentation of the solution (correct and incorrect). Only clean segments were included in the analysis (see details of the cleaning process above). Before conducting the nonphase wavelet analysis, segments were re-referenced to the average of all of the sensors at each time point. A family of Morlet wavelets was constructed at 0.5-Hz frequency intervals ranging from 1 to 30 Hz. The wavelet family was computed by using a f_0/σ_f ratio of 7 (35–37). The average power values were obtained relative to the baseline. The hypothesis for this analysis was that a burst of relative power in the θ - and α -frequency bands would be found for the incorrect solution and that this burst would parallel the ERP peak-analysis effects in time.

Subject Recruitment. Because the study involved ERPs and babies, approval was obtained from the Helsinki Committee of the Israel Ministry of Health. Families were contacted through

“Mother & Babies” health clinics. For those mothers who agreed to participate, a home visit was scheduled in which the normal development of the baby was assessed (Bayley Infant Neurodevelopmental Screening test), and mothers received a full explanation of the procedures. A total of 57 infants were tested at the ERP laboratory; all were healthy and within the normal developmental range as assessed during the home visit. Some of the infants were fussy, refused to wear the net, became tired during the session, or did not look at the screen during the trials, leaving a final group of 24 infants (14 males and 10 females) who had enough data for analysis. These infants had at least three good trials in each condition (correct/incorrect solution; mean, 7.49; range, 3–8 trials). The mean age of the infants was 7.2 months. As mentioned, a codable trial was defined as one in which the infant looked at the screen during all of the phases of the trial, thereby viewing all phases of the mathematical equation.

We thank Prof. Mary Rothbart for her valuable comments; Desiree Meloul for her help; the laboratory team, especially Liri Knopf and Michal Faroy; and the families who participated in this study. The soundtrack of the stimuli was tailor-made by the composer Mr. Yossi Yample. This work was supported by United States–Israel Binational Science Foundation Grant 2001047.

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