

PAPER

Event-related potential (ERP) indices of infants' recognition of familiar and unfamiliar objects in two and three dimensions

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Abstract

We measured infants' recognition of familiar and unfamiliar 3-D objects and their 2-D representations using event-related potentials (ERPs). Infants differentiated familiar from unfamiliar objects when viewing them in both two and three dimensions. However, differentiation between the familiar and novel objects occurred more quickly when infants viewed the object in 3-D than when they viewed 2-D representations. The results are discussed with respect to infants' recognition abilities and their understanding of real objects and representations. This is the first study using 3-D objects in conjunction with ERPs in infants, and it introduces an interesting new methodology for assessing infants' electrophysiological responses to real objects.

Introduction

ERP studies typically investigate patterns of attention and memory by showing two-dimensional representations of familiar and unfamiliar or target and nontarget objects (Curran & Friedman, 2004; Duarte, Ranganath, Winward, Hayward & Knight, 2004; Nelson, 1994, 1997; Nelson & Collins, 1991, 1992). Such studies assume that the processes involved in recognition from pictures and in the real world involve the same mechanisms. This assumption has been called into question for adults (Ittelson, 1996). Infant recognition memory research often uses pictures because more complex verbal tasks are not feasible since the subjects cannot respond verbally. There is, however, a literature suggesting that infants do not treat pictures in the same manner as adults. For example, adults can see a picture of a dog and recognize it easily as a representation of their own dog. In contrast, infants and young children do not seem to understand the relation between pictures and real objects in the way that adults do (DeLoache, Pierroutsakos & Uttal, 2003; DeLoache, Pierroutsakos, Uttal, Rosengren & Gottlieb, 1998; Pierroutsakos & DeLoache, 2003). Thus,

the 'pictorial assumption' (Ittelson, 1996, p. 176) can be challenged in work with infants.

The literature reveals that 2-D representations can be used to successfully assess infant information processing and memory. For example, Dirks and Gibson (1977) found that if 5-month-olds were familiarized to a picture of a face, they would show a novelty preference if a new person's face was perceptually different from the familiarized person's face. However, if the faces were similar, infants were less likely to show a novelty preference. Similarly, DeLoache, Strauss and Maynard (1979) found that the ability of 5-month-olds to recognize pictures extended even to line drawings, although differentiation was much stronger when infants viewed more realistic stimuli. These results suggest that infants can discriminate and remember information presented in photographs at very young ages.

However, there are also known differences in infants' behavior toward pictures and real objects, and this has led investigators to the conclusion that the understanding of pictures as symbolic representations is late and gradual in its development. DeLoache and colleagues have done the most extensive work on the development

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of infants' ability to relate symbols with their referents (e.g. DeLoache, 2000; DeLoache, Uttal & Rosengren, 2004; Pierroutsakos & DeLoache, 2003). They reported that although 9-month-olds sometimes manually manipulated pictures as if they were treating them as the three-dimensional objects they represented, 18-month-olds pointed to the pictures and did not attempt to manipulate them (DeLoache *et al.*, 1998). Although 18-month-olds appear to understand aspects of representation in ways that 9-month-olds do not, representational development is clearly not complete at this age: children under 3 years of age continue to struggle with scale models as representations (DeLoache, 2000).

To recognize familiar and unfamiliar objects from pictures, several abilities are required. Infants must have adequate perceptual abilities to distinguish two-dimensional from three-dimensional objects. This is in place within the first 6 months of life and possibly at birth (Yonas, Cleaves & Pettersen, 1978; Yonas, Elieff & Arterberry, 2002). This finding suggests that higher-order changes, rather than perception itself, may be the key development in infants' understanding of pictures.

A second aspect of infant cognitive development that must be in place is facility at relating 2-D visual input to a richer stored representation. Infants must integrate perceptual visual information about the nature of what they're looking at (a picture) with an internal representation that includes multimodal information, only some of which is likely to be perceptually available (e.g. texture, smell, etc.). Research on infants' cross-modal facility differs according to age and the tasks posed. For example, some aspects of cross-modal perception are available relatively early in development (e.g. Meltzoff, 1990; Meltzoff & Borton, 1979) while others emerge months later (Nelson, Henschel & Collins, 1993; Rose, 1977; Rose, Gottfried & Bridger, 1983). Rose and colleagues have investigated infants' ability to transfer information between real objects and their graphic representations, within (visual) and across (visual-tactile) modalities (Rose *et al.*, 1983). Infants were familiarized with objects visually (by looking at them for 30 seconds) or tactilely (by feeling them for 30 seconds). Infants who subsequently viewed the objects were able to respond preferentially to the novel object regardless of whether the test stimulus was the real object, a picture or a line drawing. Infants who familiarized tactilely only responded appropriately when the test stimulus was the real object. Further experiments showed that, given increased study time, infants in the tactile group could also preferentially attend to the novel stimulus. It is also important to note that even in the visual domain, infants who did not have adequate time for studying the familiarized object had difficulty transferring their knowledge from the familiarization to

two-dimensional representations (Rose *et al.*, 1983). These results point to the importance of encoding time in gaining a complete picture of infants' abilities to relate objects and their referents. With adequate study time, all infants are likely to show recognition or novelty preference for familiar or familiarized stimuli. However, the results of Rose and colleagues suggest that there may be developmental changes in how easily and efficiently such perceptual judgments are made.

Meltzoff (1988a) showed that infants are able to imitate televised examples of actions by 14 months of age. This suggests that infants at this age can map between 2-D images and real objects and that they can use 2-D information to guide their actions, not just their visual exploration of the 3-D world (see also Barr & Hayne, 1999). The control of action on the basis of pictorial information is yet another important aspect of 2-D to 3-D mapping.

Thus, the literature on 2-D to 3-D transfer encompasses multiple phenomena and multiple dependent measures ranging from looking time to action. It may be that there are several aspects of a complex system that, for the adult perceiver, all hang together, but develop at different times over the first 2 years of life, including: (a) being able to perceive depth and dimensions, (b) recognizing objects across modalities, (c) using 2-D displays to plan actions in the world and (d) understanding pictures as symbols that are different from the real world and yet 'stand for' it.

These developments in representational abilities lead to questions regarding the use of pictures in most ERP studies. Given that infants' treatment of 2-D representations changes with age, ERP studies that use pictures may underestimate or misestimate infants' attentional and mnemonic abilities.

We employed a recognition memory paradigm to determine whether differences exist in how infants' recognize objects from pictures versus real objects. We tested 18-month-olds because this age is similar to that described in the symbol development literature as the age at which infants show differentiated and clearly more sophisticated reactions to real objects than towards pictures (DeLoache *et al.*, 1998). At this age, infants appear to understand pictures as representations of real objects. However, some questions about the basis for this symbolic development remain unanswered. For example, although 18-month-olds clearly act as if they understand the representative nature of pictures (see DeLoache *et al.*, 1998), it is not clear how automatic this process is. The assumption is that adults know immediately that pictures are objects in their own right but also that they 'stand for' the depicted object. The goal of the present study is to describe the temporal correlates of infant recognition of real objects and

pictures at 18 months of age, an age where infants are already known to show behavioral sophistication with the stimuli (DeLoache *et al.*, 1998). In addition, this age is one in which something is known about the neural processing of objects and faces in two dimensions (Carver, Dawson, Panagiotides, Meltzoff, McPartland, Gray & Munson, 2002; Dawson, Carver, Meltzoff, Panagiotides, McPartland & Webb, 2002). Event-related potentials (ERPs) may provide a highly sensitive measure of aspects of this development. Because ERPs have very fine temporal resolution, differences between processing of pictures and real objects may be seen in such measures where none are apparent in behavioral data.

Experiment 1

Method

Participants

Sixty-one 18-month-olds were tested. Of these, 22 infants provided interpretable ERP data and constituted the final sample. Eleven of the final sample of 22 infants were girls. The mean age of the infants included was 18.35 months ($SD = .09$). Parents reported no neurological or neonatal problems with any of the children. Of the 39 infants who did not provide interpretable data, 17 did not cooperate with the testing procedure, most commonly refusing to wear the electrode cap, 17 did not provide a sufficient number of artifact-free trials for data analysis, and equipment problems were experienced during testing of an additional six infants.

Stimuli

Parents were instructed to bring one of the child's favorite toys to the testing session. Parents were given a maximum size for this toy based on what would fit in our display box, for example a tricycle would not do. They were told the dimensions of the 3-D display box and asked to identify a favorite toy in that size range. Control toys were chosen from a special lab collection that had been assembled for this purpose. These control objects were based on toys 18-month-old infants in a previous study had brought as their favorites. They were selected to represent prototypes of the categories most frequently seen in the previous study. These categories were: vehicles, musical instruments, toy telephones and balls. Each infant was shown his or her familiar toy, paired with a similar-looking unfamiliar toy in a within-subjects design. Toys were matched based on size, color and shape. An example of a child's familiar toy and a



Figure 1 Examples of matched familiar and unfamiliar objects used in recognition testing.

matching unfamiliar toy are shown in Figure 1. Before a toy was assigned as a control, the parent confirmed that their child was not familiar with it.

Parents filled out a questionnaire about their children's toy preferences. They were asked to rank the familiar toy on a 10-point scale in order of the infant's preference for it, where a rank of 1 indicated the child's most favorite toy. (Because parents were instructed not to bring very large toys, or toys with faces, the toy they brought was sometimes not the child's top-ranked favorite toy.) In addition, the toys were often of the same type as the control toys in our corpus, but were never of the identical token – that is, the unfamiliar toy was always one that the infant had never seen the specific exemplar of previously, according to parent report, although they sometimes had seen other examples from the same toy category. Parents were also instructed to indicate how long the child had owned the toy, and how often the child played with the toy. The average rating for the familiar toy was 3.4 ($SD = 2.02$), indicating that the toy was strongly preferred by the infant. Infants owned the familiar toy for an average of 8.5 months ($SD = 6.96$), and played with it an average of 5.45 days per week ($SD = 2.24$). The parents of two children in Experiment 1 did not complete the toy questionnaire.

Apparatus

The stimuli were presented using the 3-D display box (Figure 2) developed by the second author. The box was specifically designed to solve the problem of how to deliver precisely timed and alternating objects in a manner suitable for ERP studies. Objects inside it were visible only when a light within the box was illuminated. The box contained a turntable that was bisected by a

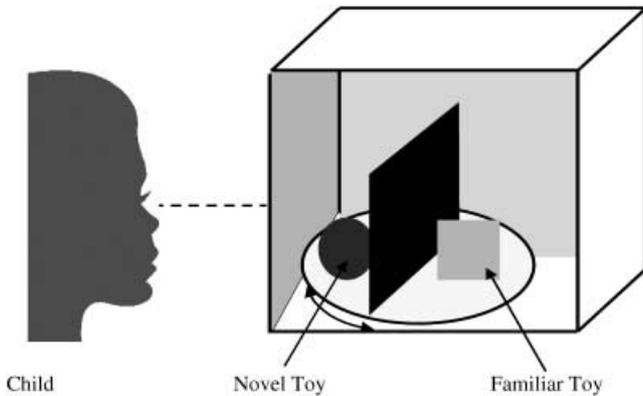


Figure 2 3-D stimulus display box designed by Meltzoff. The box contained a turntable bisected by a barrier. The familiar object was placed on one side of the barrier, and the novel object was placed on the opposite side. The turntable rotated so that either the familiar or novel object was in the front of the box. A light inside the box was illuminated, causing the object to be visible. ERPs were time-locked to the onset of the light.

dark wall. Signals from a stimulus display computer placed the turntable in either the 'familiar' or the 'unfamiliar' setting. In this way, the child could see only the familiar or the unfamiliar stimulus on any given trial. White noise was played in the room to obscure any sound that might have occurred due to the mechanism of the display box.

Procedure

After a brief (about 5-minute) warm-up period, infants were fitted with a 64-channel electrode net (EGI) (see Data collection). The child sat on the parent's lap in front of a table approximately 75 cm from the box that delivered the stimulus. The child's head was measured and the vertex was marked. An appropriate size 64-channel Geosensor EEG electrode net (Electrical Geodesics Incorporated; Tucker, 1993) was dipped into a KCl electrolyte solution that served as a conductive agent, placed on the child's head and fitted according to manufacturer's specifications. The 64 EEG electrodes cover a wide area on the scalp ranging from nasion to inion and from the right to the left ear, and are arranged uniformly and symmetrically. Impedences were measured before and after testing, and were kept below 40 k Ω . Data were collected using the vertex electrode as a reference, and were re-referenced off-line to an average reference.

Familiar (the child's toy) and unfamiliar stimuli (lab toy) were presented in random order. A large, trifold screen obscured the back of the box and the back part

of the room from the child's view. An experimenter observed the child through a peephole in the trifold screen, and signaled the computer via button press when the child was not attending. Trials on which the child did not attend were removed from the data after data collection. Data collection was terminated when the child had attended to 50 of each of the familiar and unfamiliar stimuli or when the experimenter determined that the child was no longer tolerant of the procedure.

EEG recording, editing and averaging

ERPs were time-locked to the onset of the light that revealed the contents of the box. A baseline recording of 130 milliseconds preceded stimulus onset, and the light in the box was illuminated for 500 milliseconds. ERP data were recorded for an additional 1200 milliseconds following stimulus offset. The intertrial interval varied randomly between 1000 and 2000 milliseconds. The signal was amplified and filtered via a preamplifier system (Electrical Geodesics Incorporated). The amplification was set at 1000 \times and filtering was done through a .1 Hz high-pass filter and a 100 Hz elliptical low-pass filter. The conditioned signal was multiplexed and digitized at 250 samples per second via an Analog-to-Digital converter (National Instruments PCI-1200) positioned in an Apple Macintosh computer dedicated to data collection. Data were recorded continuously and streamed to the computer's hard disk. The timing of the stimulus onset and offset were registered together with the electrophysiological record for off-line segmentation of the data.

Algorithms were applied to correct for baseline shifts and to digitally filter data (low-pass Butterworth filter of 20 Hz) to reduce environmental noise artifact. Artifact was defined as including electrodes for which the weighted running average exceeded 150 microvolts for transit and 50 microvolts for voltage. This method rejects both high frequency artifact and low frequency drift, as well as sharp transitions in the data. Trials that included EOG artifact, defined as activity exceeding 150 microvolts or a deviation in running averages exceeding 150 microvolts, were also rejected. Data from individual electrodes were rejected if the electrode failed to meet these criteria, and trials that included more than 10 electrodes with artifact were rejected. In addition, an algorithm that interpolates values from neighboring electrodes was used to replace electrodes for which more than 25% of trials were rejected because of artifact. All participants whose data were included in the final sample had at least nine artifact-free trials in each condition (familiar toy, unfamiliar toy). The average number of artifact free trials was 19.86 (SD = 7.34) for the familiar stimulus and 19.95 (SD = 7.83) for the unfamiliar stimulus.

Results

Components

Grand average ERP waveforms are displayed in Figure 3. Four components of interest were observed in Experiment 1. An early positive component that peaked at about 200 milliseconds (the P2 component) after stimulus onset was observed over parietal scalp locations. This component was followed by a negative component that peaked at about 250 milliseconds, also over parietal scalp locations (the N2 component). A middle-latency positive component was observed that peaked at about 480 milliseconds over parietal scalp locations (the P400 component). Finally, a middle-latency negative component was observed that peaked at about 500 milliseconds over frontal scalp locations (the Nc component). Table 1 shows the mean amplitudes of each component for familiar and unfamiliar stimuli. We examined the effects of familiarity (familiar and unfamiliar) and hemisphere (left, right, where appropriate) on the amplitude and latency of each component using repeated-measures ANOVAs. Data were collapsed across clusters of electrodes as shown in Figure 3. These analyses are described below.

P2 component. Over midline parietal scalp locations, the one-way repeated-measures ANOVA revealed a main effect of condition that approached significance for the amplitude of the P2 component, $F(1, 21) = 3.07, p = .09$. The P2 response was larger to the familiar toy than to the unfamiliar toy. No significant effects related to the latency to peak of the P2 component were observed at midline scalp locations (all $ps > .10$).

Over lateral scalp locations, the 2 (Condition: familiar, unfamiliar) \times 2 (Hemisphere: left, right) way ANOVA revealed a main effect of condition for the amplitude of the P2 component, $F(1, 21) = 5.47, p < .03$. This main effect of condition was qualified by a condition by hemisphere interaction, $F(1, 22) = 5.48, p < .03$. A follow-up one-way ANOVA showed that the P2 response was larger to the familiar toy than to the unfamiliar toy over the right hemisphere, $F(1, 21) = 10.44, p < .01$. There was not a significant difference between the response to the familiar and unfamiliar toys over the left hemisphere, $F(1, 21) = .24$. No significant effects related to the latency to peak of the P2 component were observed at midline scalp locations (all $ps > .05$).

N2 component. At midline parietal scalp locations, a main effect of condition was observed for the amplitude of the N2 component, $F(1, 21) = 4.40, p < .05$. The component was more negative in response to the unfamiliar toy than to the familiar toy. No significant effects related

Table 1 Amplitude (SD) of components in Experiments 1 and 2

Experiment	P2 component			N2 component			P400 component			Nc component		
	Familiar	Unfamiliar	<i>p</i>	Familiar	Familiar	Familiar	Familiar	Unfamiliar	<i>p</i>	Familiar	Unfamiliar	<i>p</i>
Experiment 1												
<i>3-D</i>												
Midline	7.57 (4.92)	5.35 (5.25)	.09	-13.33 (6.2)	-13.33 (6.2)	-13.33 (6.2)	18.06 (7.25)	15.07 (6.86)	.07	-13.33 (6.2)	-12.82 (5.94)	ns
Lateral	8.62 (5.81)	6.15 (5.0)	.03*	-10.11 (6.87)	-10.11 (6.87)	-10.11 (6.87)	17.31 (8.04)	16.11 (7.69)	ns	-10.11 (6.87)	-10.80 (6.76)	ns
Experiment 2												
<i>2-D</i>												
Midline	10.22 (5.73)	8.90 (5.86)	ns	-17.17 (5.59)	-17.17 (5.59)	-17.17 (5.59)	19.92 (6.24)	15.93 (6.47)	.02*	-17.17 (5.59)	-13.87 (5.59)	.01*
Lateral	10.01 (7.46)	9.28 (6.98)	ns	-11.31 (6.32)	-11.31 (6.32)	-11.31 (6.32)	21.95 (8.21)	20.01 (8.36)	ns	-11.31 (6.32)	-11.20 (6.21)	ns
<i>3-D</i>												
Midline	8.56 (4.46)	7.04 (6.12)	ns	-13.95 (4.53)	-13.95 (4.53)	-13.95 (4.53)	15.43 (6.54)	12.20 (7.69)	.08	-13.95 (4.53)	-13.57 (4.56)	ns
Lateral	10.14 (7.55)	8.71 (7.39)	.03*	-8.61 (5.84)	-8.61 (5.84)	-8.61 (5.84)	20.62 (10.31)	17.85 (8.28)	.08	-8.61 (5.84)	-7.28 (5.32)	.10

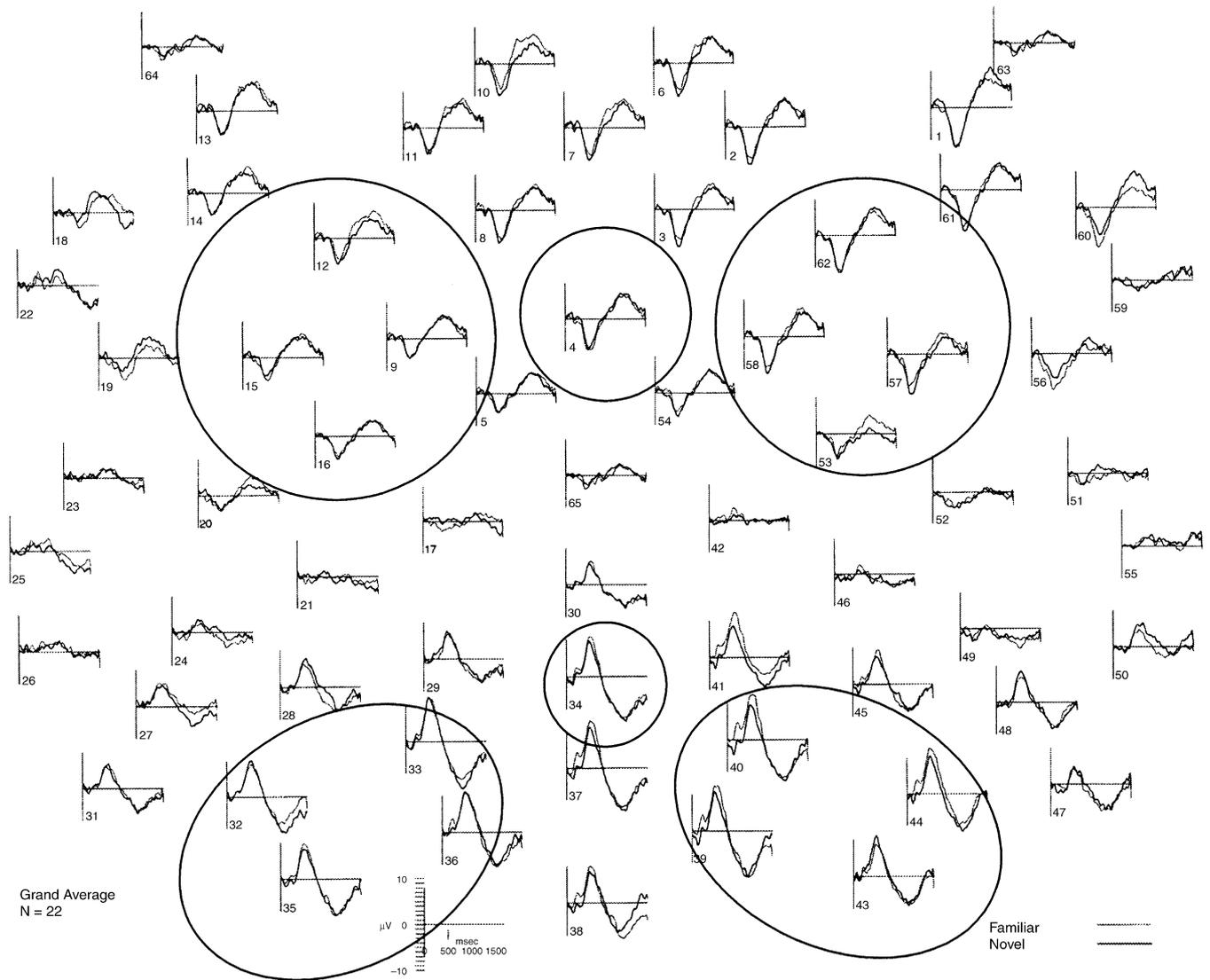


Figure 3 Grand Average ERP waveforms for Experiment 1. The Nc component was analyzed at midline frontal electrodes. The P2, N2 and P400 components were analyzed at posterior electrodes.

to the latency to peak of the N2 component were observed at midline scalp locations (all $ps > .05$).

At lateral scalp locations, a condition by hemisphere interaction was observed for the amplitude of the N2 component. Over the right hemisphere, the response to the unfamiliar toy was more negative than to the familiar toy, $F(1, 21) = 10.85$, $p < .01$. There was no difference in the response to the familiar versus the novel toy over the left hemisphere, $F(1, 21) = .12$. No significant effects related to the latency to peak of the N2 component were observed at lateral scalp locations (all $ps > .05$).

P400 component. At midline parietal scalp locations, a main effect of condition was observed that approached significance, $F(1, 21) = 3.42$, $p = .08$, with the amplitude

of the P400 response being larger to the familiar than to the unfamiliar toy. For the latency to peak of the P400 component, a main effect of condition was observed, $F(1, 21) = 10.16$, $p < .01$. The P400 component peaked more quickly in response to the unfamiliar toy (mean latency = 450 milliseconds, $SD = 55.04$) than to the familiar toy (mean latency = 505.64 milliseconds, $SD = 48.4$).

No significant effects of condition, hemisphere or condition by hemisphere interactions were observed for the amplitude and latency of the P400 component at lateral parietal scalp locations (all $ps > .05$).

Nc component. No significant effects were observed in the amplitude or latency of the Nc component at midline or lateral scalp locations (all $ps > .05$).

Discussion

The results of Experiment 1 suggest that 18-month-olds differentiate familiar from unfamiliar real objects in early exogenous ERP components (e.g. the N2). Previous studies (all using 2-D pictures) have shown ERP differences to familiar and unfamiliar objects in middle latency components, but not in early exogenous sensory components (Carver, Bauer & Nelson, 2000; Carver *et al.*, 2002; Dawson *et al.*, 2002; de Haan & Nelson, 1999; Nelson & Collins, 1991). One possible interpretation of this result is that the amount of time required to recognize real objects is short, and that infants require less time to compute the difference in familiar and unfamiliar stimuli than has been indicated in previous research. In Experiment 1, we did not directly test this hypothesis. It may be that previous researchers did not analyze early components, but that there were, nevertheless, differences in these components. The purpose of Experiment 2 was to randomly assign infants to either a 2-D (picture) or 3-D (real object) condition to directly evaluate differences in ERP activity when viewing familiar and unfamiliar objects.

Experiment 2

Method

Participants

Eighteen-month-old infants were randomly assigned to either the 2-D or 3-D condition. Infants in each group were tested on the within-subject variable of familiar vs. novel toys, as described in Experiment 1. Seventeen infants (nine girls) provided interpretable ERP data in the 2-D group (mean age = 18.37 months, $SD = .09$) and 16 infants (eight girls) did so in the 3-D group (mean age = 18.36 months, $SD = .15$). Parents reported no neurological or neonatal problems with any of the children.

Of the infants who did not provide interpretable data, 26 did not cooperate with the testing procedure (2-D = 11, 3-D = 15), 36 did not provide a sufficient number of artifact-free trials for data analysis (2-D = 24, 3-D = 12) and 17 experienced equipment problems during testing (2-D = 8, 3-D = 9). One additional child was tested in the 3-D group but was not included in the final sample because there had been medical complications during early infancy.

Stimuli

The stimuli were collected and matched with control toys in the same fashion as for Experiment 1. Infants' toys from home were matched with similar-looking toys from a lab

collection that were chosen based on previous studies. For the 3-D group, the toys were displayed in the stimulus display box, as described above in Experiment 1. The control toy was selected to be of the same approximate size, shape and color as the child's familiar toy (see Figure 1). In both the 3-D and 2-D stimulus dimension groups, toys were constrained to fit within the stimulus display box, and were matched for size, shape and color. Thus, although the size of the stimuli was not specifically matched between groups and conditions, the criteria served to ensure that the size of toys was matched within these factors. For the 2-D group, digital pictures were taken of the child's toy and the control toy against the same grey background. The digital image was manipulated so that the dimensions were approximately equivalent for both the familiar and novel condition and was approximately 15 by 15 cm for square shaped toys or 10 by 18 cm for rectangular toys. The digital images were presented on a computer screen (see Apparatus, below). The parent of one child in the 3-D condition did not complete the toy questionnaire. The preference rating for infants in the 2-D group was 3.8 ($SD = 4.38$). Infants in this group owned the favorite toys for an average of 9.4 months ($SD = 6.82$) and played with them 5.5 days per week ($SD = 2.19$). The preference rating for infants in the 3-D group was 3.4 ($SD = 1.98$). Infants in this group owned the toys for an average of 8.4 months ($SD = 6.16$) and played with them an average of 6.08 days per week ($SD = 1.94$). There were no differences in the preference ratings, duration of ownership, or frequency of play between Experiment 1 and Experiment 2 or between the 2-D and 3-D conditions (all $ps > .40$).

Apparatus

The same 3-D apparatus was used for displaying 3-D stimuli as in Experiment 1. In the 2-D condition, stimuli were displayed as pictures rather than in three dimensions. Digitized images of the child's toy and an unfamiliar toy were shown on a 17-inch computer monitor placed about 75 cm away from the child. The position of the video monitor was identical to that of the front of the 3-D display box in Experiment 1 and in the 3-D condition in Experiment 2. Identical white noise was played in both the 2-D and 3-D conditions.

Data collection

Data collection procedures were identical in Experiments 1 and 2.

EEG recording, editing and averaging

EEG recording, editing and averaging were identical to the procedures described for Experiment 1, above.

Data reduction

Data were reduced as described for Experiment 1, above. All participants whose data were included in the final sample had at least nine artifact-free trials in each condition. The average number of trials for infants in the 2-D group was 18.82 (SD = 7.2) for the familiar stimulus and 19.69 (SD = 6.52) for the unfamiliar stimulus. The average number of trials for infants in the 3-D group was 21.13 (SD = 10.97) for the familiar stimulus and 23 (SD = 9.85) for the unfamiliar stimulus. One-way ANOVAs revealed no significant differences in the number of trials between conditions or between groups, or between Experiments 1 and 2 (all $ps > .05$).

Results

Grand average ERP waveforms for Experiment 2 are displayed in Figures 4 (2-D) and 5 (3-D). For midline scalp locations, a 2 (Familiarity: familiar, unfamiliar) \times 2 (Stimulus dimension: 2-D, 3-D) ANOVA was conducted for the amplitude and latency of each component (P2, N2, Nc, P500). At lateral scalp locations, a 2 (Hemisphere: right, left) by 2 (Familiarity: Familiar, Unfamiliar) \times 2 (Stimulus dimension: 2-D, 3-D) repeated-measures ANOVA was conducted.

P2 component. At midline scalp locations, there were no significant effects of condition for the 2-D and 3-D groups for the amplitude or latency of the P2 component. At lateral scalp locations, a hemisphere by stimulus dimension by familiarity interaction was observed, $F(1, 31) = 4.18, p < .05$. The P2 component for infants in the 3-D group differentiated familiar from unfamiliar stimuli over the left hemisphere, $F(1, 15) = 5.07, p < .05$, whereas no differences were observed for the hemisphere or familiarity variables for infants in the 2-D group (all $ps > .05$). There were no effects of familiarity or hemisphere on the latency of the P2 component across stimulus dimensions (all $ps > .05$).

N2 component. At midline scalp locations, no significant effects of familiarity were observed for the 2-D and 3-D groups (all $ps > .05$). At lateral scalp locations, a three-way Hemisphere \times Familiarity \times Stimulus dimension interaction was observed, $F(1, 31) = 6.85, p < .01$. The N2 component for infants in the 3-D group differentiated familiar from unfamiliar stimuli over the left hemisphere, $F(1, 15) = 8.14, p < .01$. No differences in either dependent measure were observed for the hemisphere or familiarity variable for infants in the 2-D group (all $ps > .05$). For the latency of the N2 component, a hemisphere by familiarity interaction was

observed, $F(1, 31) = 5.94, p < .05$. Over the right hemisphere, the N2 component peaked earlier for the unfamiliar toy than for the familiar toy. Over the left hemisphere, the opposite pattern was observed. However, neither of these effects reached statistical significance, $F(1, 31) = 2.49, p = .12$ over right hemisphere, $F(1, 31) = 2.21, p = .15$ over left hemisphere.

P400 component. At midline scalp locations, a main effect of stimulus dimension was observed, $F(1, 31) = 4.01, p < .05$. The P400 response was larger for infants in the 2-D group than for infants in the 3-D group. A main effect of familiarity was also seen, $F(1, 31) = 9.96, p < .01$. For infants in both groups, the response to the familiar toy was larger than the response to the unfamiliar toy. There were no effects on the latency of the P400 at midline scalp locations (all $ps > .05$).

At the lateral scalp locations, a main effect of familiarity was also seen, $F(1, 31) = 4.94, p < .05$. As for midline scalp locations, the response was larger to familiar than to unfamiliar toys regardless of whether the child saw the toys displayed in two or three dimensions. No effects of familiarity or hemisphere were observed on the latency of the P400 component (all $ps > .05$).

Nc component. At midline scalp locations, a main effect of familiarity was observed, $F(1, 31) = 6.25, p < .02$. Across groups, the amplitude of the Nc component was larger to the familiar than to the unfamiliar toy. In addition, a Familiarity by Stimulus dimension interaction that approached statistical significance was also observed, $F(1, 31) = 3.96, p = .055$. The difference between the amplitude of the Nc for familiar and unfamiliar toys was significant only for the infants in the 2-D group.

At lateral scalp locations, a main effect of stimulus dimension was observed, $F(1, 31) = 4.61, p < .05$. The Nc response was larger for the infants in the 2-D group than for infants in the 3-D group. In addition, a Group by Familiarity by Hemisphere interaction was also observed, $F(1, 31) = 6.79, p < .02$. Follow-up ANOVAs revealed a Familiarity by Group interaction over the right hemisphere, $F(1, 31) = 6.17, p < .02$, and a main effect of group over the left hemisphere, $F(1, 31) = 13.63, p < .001$. Over the right hemisphere, the Nc response was non-significantly larger to the familiar than to the unfamiliar toy, $F(1, 16) = 4.27, p = .06$, for infants in the 3-D group. There was no difference between the amplitude to the familiar and unfamiliar toys for infants in the 2-D group ($p > .05$). Over the left hemisphere, the Nc response was larger for infants in the 2-D group than for infants in the 3-D group. No effects were seen on the latency of the Nc component between groups (all $ps > .05$).

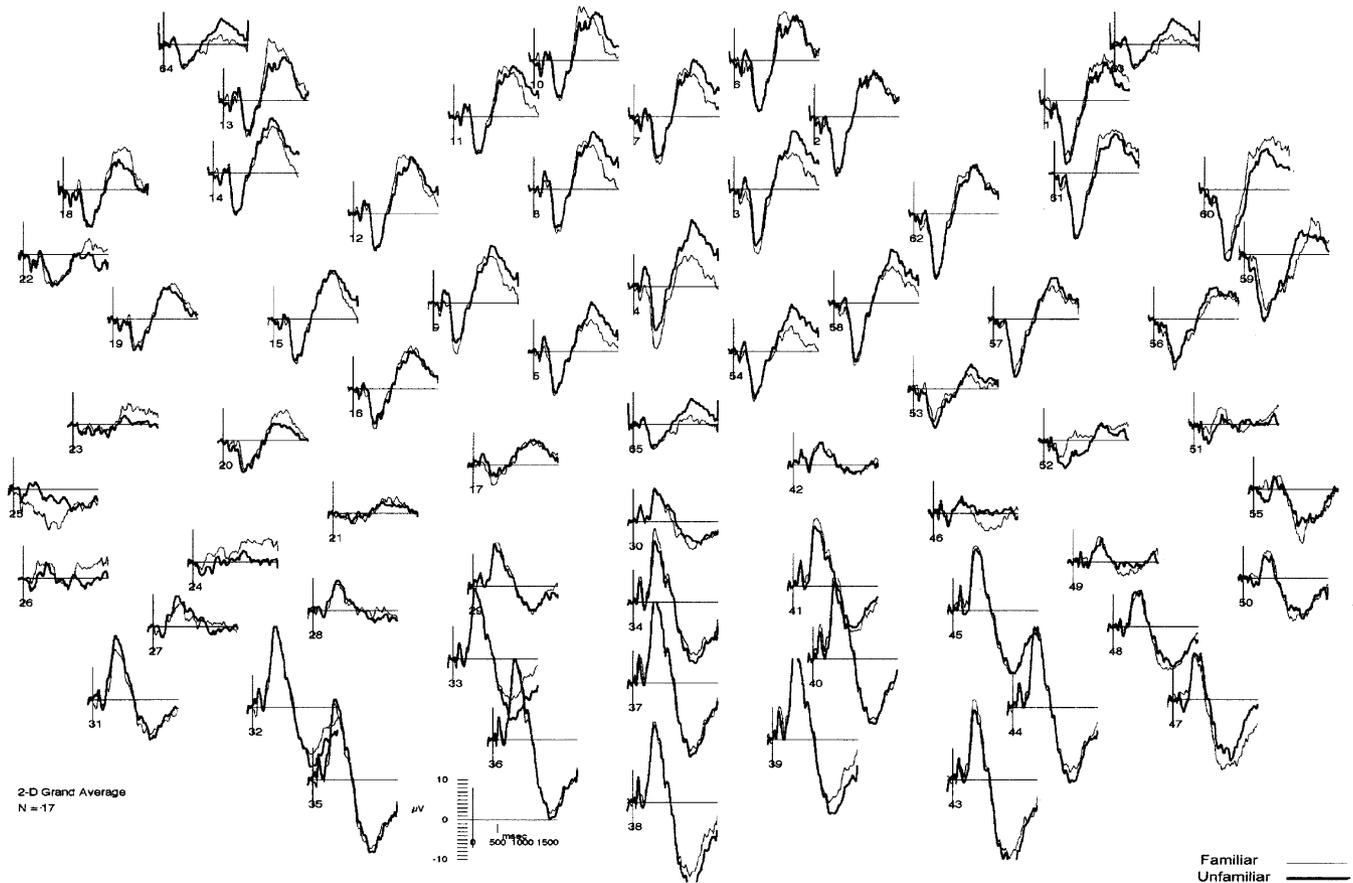


Figure 4 Grand Average ERP waveforms for the 2-D group in Experiment 2.

Discussion

The results are consistent with previous research that shows that 18-month-old toddlers can recognize familiar versus unfamiliar objects from pictures. Both groups in the current study showed differentiation of familiar and novel stimuli in both conditions. However, in the group that viewed the real objects, differentiation occurred in an early exogenous sensory component (N2) whereas in the group that observed the pictures, the differentiation did not come until a middle latency attention component (Nc). Thus, although both groups appeared able to distinguish familiar and unfamiliar objects, more processing time was required to make this distinction in infants who viewed pictures.

General discussion

The results of this neurophysiological study indicate that even at 18 months of age, infants are less adept at recognizing highly familiar versus unfamiliar toys in two

versus three dimensions. They are able to make the familiar–unfamiliar toy distinction extremely quickly, when they are presented as real objects. However, when the highly familiar and unfamiliar stimuli are presented as two-dimensional representations, infants are less efficient in differentiating them. Although infants show neurophysiological responses consistent with attentional differences between familiar and unfamiliar objects regardless of how they are displayed, these differences occur much faster and in earlier ERP components when infants view ‘the real thing’. The results of Experiment 1 suggest that 18-month-olds more quickly process differences between familiar and unfamiliar objects when they view those objects in three rather than two dimensions. The results of Experiment 2 replicate these findings, and indicate that the effect of familiarity on early ERP components occurs only for the infants who viewed real objects.

These results are consistent with behavioral results observed by Rose *et al.* (1983). The timing and nature of infants’ exposure to objects is an important factor in the ease with which those objects affect infants’ behavioral

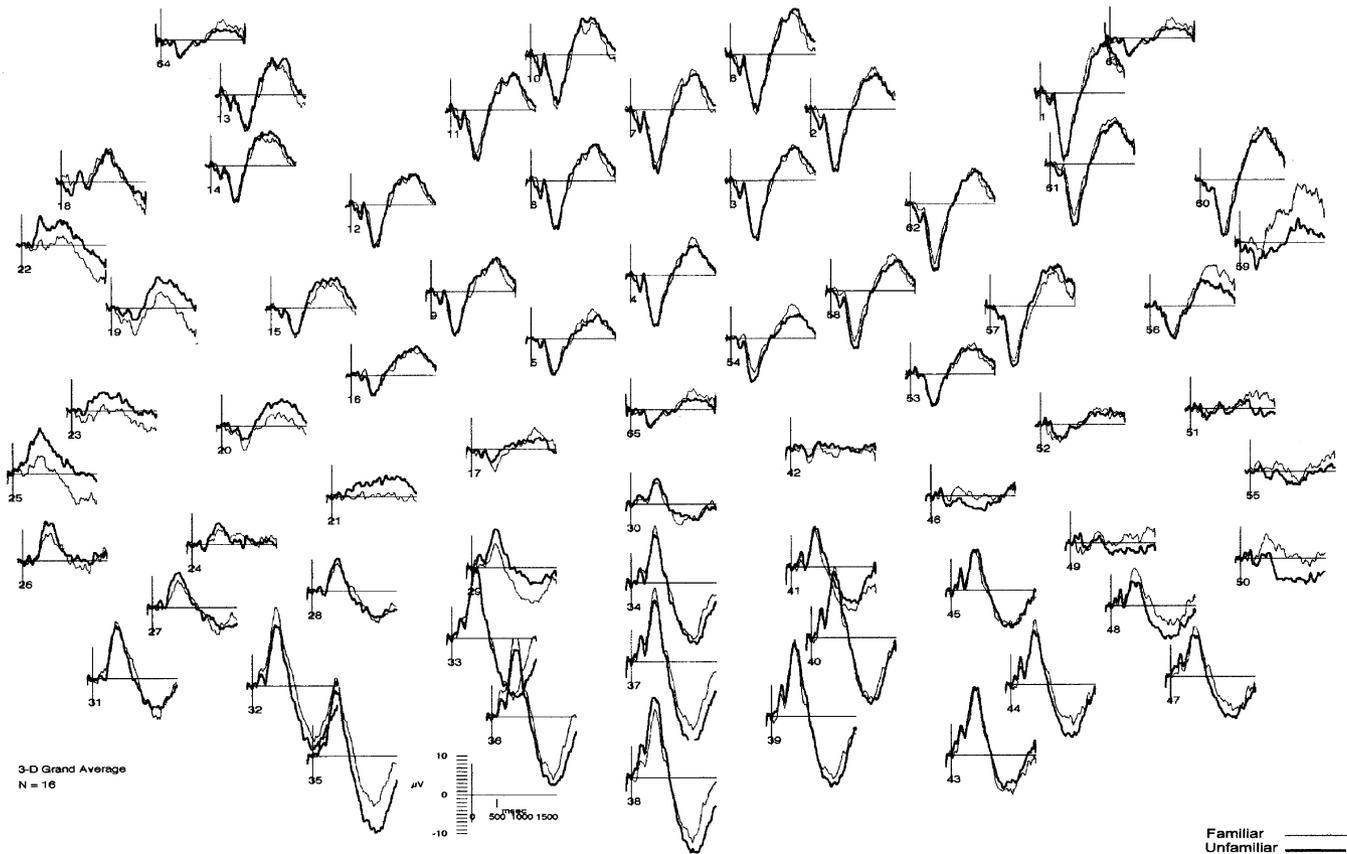


Figure 5 Grand Average ERP waveforms for the 3-D group in Experiment 2.

responses. It may be that similar processes might be important in older children: children all show recognition of familiar objects, but the timing of that recognition is affected by the dimensionality in which the infant sees the stimulus. Infants may require additional processing of pictures in order to recognize them as representations of the objects they stand for, and only then can they recognize them as familiar or not. This time delay is small, and it is unlikely that it would be apparent in behavioral manipulations with children as old as 18 months of age. However, ERP allows for millisecond timing of neural events, and thus provides a mechanism by which discrete differences can be observed.

Previous studies have shown temporal differences in effects of real objects versus pictures on recognition memory (Rose *et al.*, 1983), although on a different time scale. Some of the same mechanisms might be at work in the present study. It takes infants milliseconds longer to detect familiarity, which may translate into a longer time to habituate to the stimuli, as was seen by Rose and colleagues (1983). At this point, it is unclear what the mechanism for this effect on processing time might be. Perhaps when it takes infants longer to recognize something as familiar

(on the order of milliseconds), that translates somehow into a less 'solid' representation, so they need more exposure time to reach 'familiarity' in a pre-exposure visual or tactile task. Future research should directly test this hypothesis, perhaps by combining the neurophysiological methods used here and the behavioral methods employed by Rose and colleagues.

Because of the precise temporal resolution of ERPs, we have been able to show differences in how infants process familiar and unfamiliar real objects and pictures. These results raise several interesting questions. The infants in the present study were at an age where other research has suggested they are beginning to understand the symbolic nature of pictures (DeLoache *et al.*, 1998). Younger infants, in whom behavioral indices of such understanding are not apparent, might show different patterns of ERP activity. Future research should use ERPs to address the question of recognition from pictures and real objects in infants who treat these stimuli similarly (e.g. 9-month-olds). In addition, given that representational development continues after 18 months of age (DeLoache *et al.*, 2004), studies tracking ERP responses to 2-D and 3-D stimuli beyond this age would be useful as well.

The results suggest that 18-month-old toddlers recognize familiar/favorite toys (vs. unfamiliar ones), even when the stimulus is a 2-D image of that favorite toy. This finding is consistent with previous ERP and preferential-looking studies (Dawson *et al.*, 2002; de Haan & Nelson, 1999; DeLoache *et al.*, 1979; Dirks & Gibson, 1977) and also with previous results showing that infants can use 2-D displays as a basis for imitating with 3-D objects in the real world (Barr & Hayne, 1999; Meltzoff, 1988a). All of this research indicates a mapping from the 2-D to the 3-D world. However, in the group of infants that viewed the real objects, differentiation occurred in an early exogenous sensory component (N2) whereas in the group that observed the pictures, the differentiation did not come until a middle latency attention component (Nc). Thus, although both groups appeared able to distinguish familiar and unfamiliar objects, more processing time was required to make this distinction in infants who viewed pictures.

The results also raise the issue of the neural processing of pictorial symbols in adults. Although adults clearly have no problem recognizing a familiar representation as familiar, what are the temporal events that lead up to that recognition? Do adults, as infants, process pictures differently from the real objects they represent? All previous data from studies of adults, children and infants have been conducted using two-dimensional stimuli. The present findings make it clear that ERP responses to 2-D stimuli are not identical to responses to 3-D stimuli. Thus, our understanding of the neural events correlated with recognition and/or attention may need to be re-examined and expanded to acknowledge that heretofore neuroscience theories have been based largely on the brain's responses to 2-D pictures.

In addition, using ERP responses, much of what we understand about adult attention (Hillyard & Anillo-Vento, 1998) and memory (e.g. Curran & Friedman, 2004; Curran, Schacter, Johnson & Spinks, 2001) also comes from studies using 2-D stimuli. It is unclear how adults would respond in paradigms like the present one (such studies are under way). However, if differences in processing 2-D and 3-D stimuli were also found in adults, the results would require us to consider that the function of several ERP components might be different than we previously thought, and, in addition, may vary depending on the nature of the paradigm used. Moreover, variables such as selective attention and task relevance, which are thought to modulate the activity of commonly reported ERP waveforms (e.g. the P300), may have different effects on components that are differently elicited or affected by the presentation of 2-D rather than 3-D stimuli.

Researchers have drawn conclusions about developmental change in the brain system that controls long-term

explicit memory because of the results of ERP studies of infants' responses to previously seen versus unseen events. For example, when infants view pictures taken from events they have seen before versus events they have not seen before in an imitation paradigm, individual differences in ERP responses correspond to individual differences in performance on the imitation task (Bauer, Wiebe, Carver, Waters & Nelson, 2003; Carver *et al.*, 2000). The relation between these indices of recall and recognition memory also change with age. Whereas 9-month-olds show increased ERP amplitude to new events compared to old events, 10-month-olds show the opposite pattern (Bauer, Wiebe, Carver, Lukowski, Haight, Waters & Nelson, *in press*). The results of these studies have been interpreted as evidence of the new emergence of the long-term explicit memory brain system only at the end of the first year of life (Bauer *et al.*, *in press*; Bauer *et al.*, 2003; Carver & Bauer, 2001; Carver *et al.*, 2000; but see Meltzoff, 1988b, 1990, 2004, for arguments that such memory emerges earlier). However, the late-emergence hypothesis was based in part on studies using 2-D stimuli. The present results suggest that infants' brain responses to familiar and unfamiliar 3-D objects are different than to 2-D pictures. Thus, we may be underestimating infants' ability to recognize stimuli by using only stimuli that elicit differences in later ERP components.

In studies of both infants and adults, the results of experiments conducted using 2-D stimuli are limited by the nature of the stimuli. Studies using 3-D stimuli, such as the experiment described here, can provide a more 'real-world' perspective on the activation of brain systems in different paradigms. The method that we have developed will be a useful tool in future studies of attention and memory and will be broadly applicable in studies of the brain basis of attention and memory and their development.

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References

- Barr, R., & Hayne, H. (1999). Developmental changes in imitation from television during infancy. *Child Development*, *70*, 1067–1081.

- Bauer, P.J., Wiebe, S.A., Carver, L.J., Lukowski, A.F., Haight, J.C., Waters, J.M., & Nelson, C.A. (in press). Electrophysiological indices of encoding and behavioral indices of recall: examining relations and developmental change late in the first year of life. *Developmental Neuropsychology*.
- Bauer, P.J., Wiebe, S.A., Carver, L.J., Waters, J.M., & Nelson, C.A. (2003). Developments in long-term explicit memory late in the first year of life: behavioral and electrophysiological indices. *Psychological Science*, **14**, 629–635.
- Carver, L.J., & Bauer, P.J. (2001). The dawning of a past: the emergence of long-term explicit memory in infancy. *Journal of Experimental Psychology: General*, **130**, 726–745.
- Carver, L.J., Bauer, P.J., & Nelson, C.A. (2000). Associations between infant brain activity and recall memory. *Developmental Science*, **3**, 234–246.
- Carver, L.J., Dawson, G., Panagiotides, H., Meltzoff, A.N., McPartland, J., Gray, J., & Munson, J. (2002). Age-related differences in neural correlates of face recognition during the toddler and preschool years. *Developmental Psychobiology*, **42**, 148–159.
- Curran, T., & Friedman, W.J. (2004). ERP old/new effects at different retention intervals in recency discrimination tasks. *Cognitive Brain Research*, **18**, 107–120.
- Curran, T., Schacter, D.L., Johnson, M.K., & Spinks, R. (2001). Brain potentials reflect behavioral differences in true and false recognition. *Journal of Cognitive Neuroscience*, **13**, 201–216.
- Dawson, G., Carver, L.J., Meltzoff, A.N., Panagiotides, H., McPartland, J., & Webb, S.J. (2002). Neural correlates of face and object recognition in young children with autism spectrum disorder, developmental delay, and typical development. *Child Development*, **73**, 700–717.
- de Haan, M., & Nelson, C.A. (1999). Brain activity differentiates face and object processing in 6-month-old infants. *Developmental Psychology*, **35**, 1113–1121.
- DeLoache, J.S. (2000). Dual representation and young children's use of scale models. *Child Development*, **71**, 329–338.
- DeLoache, J.S., Pierroutsakos, S.L., & Uttal, D.H. (2003). The origins of pictorial competence. *Current Directions in Psychological Science*, **12**, 114–118.
- DeLoache, J.S., Pierroutsakos, S.L., Uttal, D.H., Rosengren, K.S., & Gottlieb, A. (1998). Grasping the nature of pictures. *Psychological Science*, **9**, 205–210.
- DeLoache, J.S., Strauss, M.S., & Maynard, J. (1979). Picture perception in infancy. *Infant Behavior and Development*, **2**, 77–89.
- DeLoache, J.S., Uttal, D.H., & Rosengren, K.S. (2004). Scale errors offer evidence for a perception–action dissociation early in life. *Science*, **304**, 1027–1029.
- Dirks, J., & Gibson, E.J. (1977). Infants' perception of similarity between live people and their photographs. *Child Development*, **48**, 124–130.
- Duarte, A., Ranganath, C., Winward, L., Hayward, D., & Knight, R.T. (2004). Dissociable neural correlates for familiarity and recollection during the encoding and retrieval of pictures. *Cognitive Brain Research*, **18**, 255–272.
- Hillyard, S.A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences*, **95**, 781–787.
- Ittelson, W.H. (1996). Visual perception of markings. *Psychonomic Bulletin and Review*, **3**, 171–187.
- Meltzoff, A.N. (1988a). Imitation of televised models by infants. *Child Development*, **59**, 1221–1229.
- Meltzoff, A.N. (1988b). Infant imitation and memory: nine-month-olds in immediate and deferred tests. *Child Development*, **59**, 217–225.
- Meltzoff, A.N. (1990). Towards a developmental cognitive science: the implications of cross-modal matching and imitation for the development of representation and memory in infancy. In A. Diamond (Ed.), *The development and neural bases of higher cognitive functions*, *Annals of the New York Academy of Sciences* (Vol. 608, pp. 1–31). New York: New York Academy of Sciences.
- Meltzoff, A.N. (2004). The case for developmental cognitive science: theories of people and things. In G. Bremner & A. Slater (Eds.), *Theories of infant development* (pp. 145–173). Oxford: Blackwell Publishing.
- Meltzoff, A.N., & Borton, R.W. (1979). Intermodal matching by human neonates. *Nature*, **282**, 403–404.
- Nelson, C.A. (1994). Neural correlates of recognition memory in the first postnatal year. In G. Dawson & K.M. Fischer (Eds.), *Human behavior and the developing brain* (pp. 269–313). New York: Guilford Press.
- Nelson, C.A. (1997). The neurobiological basis of early memory development. In N. Cowan (Ed.), *The development of memory in childhood*. Hove: Psychology Press.
- Nelson, C.A., & Collins, P.F. (1992). Neural and behavioral correlates of visual recognition memory in 4- and 8-month-old infants. *Brain and Cognition*, **19**, 105–121.
- Nelson, C.A., & Collins, P.F. (1991). Event-related potential and looking-time analysis of infants' responses to familiar and novel events: implications for visual recognition memory. *Developmental Psychology*, **27**, 50–58.
- Nelson, C.A., Henschel, M., & Collins, P.F. (1993). Neural correlates of cross-modal recognition memory by 8-month-old infants. *Developmental Psychology*, **29**, 411–420.
- Pierroutsakos, S.L., & DeLoache, J.S. (2003). Infants' manual exploration of pictorial objects varying in realism. *Infancy*, **4**, 141–156.
- Rose, S.A. (1977). Infants' transfer of response between two-dimensional and three-dimensional stimuli. *Child Development*, **48**, 1086–1091.
- Rose, S.A., Gottfried, A.W., & Bridger, W.H. (1983). Infants' cross-modal transfer from solid objects to their graphic representations. *Child Development*, **54**, 686–694.
- Tucker, D.M. (1993). Spatial sampling of head electrical fields: the geodesic sensor net. *Electroencephalography and Clinical Neurophysiology*, **87**, 154–163.
- Yonas, A., Cleaves, W., & Pettersen, L. (1978). Development of sensitivity to pictorial depth. *Science*, **200**, 77–79.
- Yonas, A., Elieff, C.A., & Arterberry, M.E. (2002). Emergence of sensitivity to pictorial depth cues: charting development in individual infants. *Infant Behavior and Development*, **25**, 495–514.

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