

# The Neural Basis of Perceptual Category Learning in Human Infants

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## Abstract

■ We measured looking times and ERPs to examine the cognitive and brain bases of perceptual category learning in 6-month-old infants. In Experiment 1, we showed that categorization and exemplar discrimination rely on different cortical processes. Specifically, the repetition of individual exemplars resulted in differential cortical processing at posterior channels at an early stage during object processing (100–300 msec), whereas discriminating among members of different categories was reflected in ERP differences over anterior cortical regions occurring later in time (300–500 msec) than the repetition effects. In Experiment 2,

replicating the findings of Study 1, we found that infants engage the same cortical processes to categorize visual objects into basic-level categories, regardless of whether a basic (bird vs. fish) or global level is crossed (birds vs. cars). This pattern of findings is consistent with perceptual accounts of infant categorization [Quinn, P. C., & Eimas, P. D. Perceptual organization and categorization in young infants. In C. Rovee-Collier & L. P. Lipsitt (Eds.), *Advances in infancy research* (Vol. 10, pp. 1–36). Norwood, NJ: Ablex, 1996] and accords with recent adult neural-level models of perceptual categorization. ■

## INTRODUCTION

Categorization, the ability to recognize physically different objects as members of the same group, is a powerful process that helps us to structure and understand our environment. From insects to primates, categorization is evident across a broad range of animal species (Freedman & Miller, 2008). However, whereas in mammals and birds many categories are learned, in insects, reptiles, and amphibians, adaptive categorization is genetically determined (e.g., Wytenbach, May, & Hoy, 1996). The capacity to learn categories and to use this knowledge flexibly plays an important role in inference, prediction, decision-making, and language acquisition, and is thus integral to all kinds of human behavior.

One important aspect of categorization is our ability to group objects at different levels of abstraction. Adult category representations are organized hierarchically; while maintaining the ability to discriminate individual exemplars, we make basic-level distinctions as between birds and fish, global-level distinctions as between animals and vehicles, and subordinate-level distinctions as between robins and sparrows (Curran, Tanaka, & Weiskopf, 2002; Rosch & Lloyd, 1978). There is work to suggest that different brain and cognitive processes might allow for categorization at different levels of the hierarchy in adults (Tanaka, Luu, Weisbrod, & Kiefer, 1999).

Although there is behavioral evidence that from very early in life human infants are able to learn new categories (see Mareschal & Quinn, 2001 for a review), little is known about the neural basis of perceptual categorization in infancy. Because disentangling bottom-up and top-down processing in adult category learning is notoriously difficult, studying category learning in prelinguistic infants that have little or no prior knowledge of the many categories in their environment provides a unique way of exploring natural perceptual category learning (French, Mareschal, Mermillod, & Quinn, 2004). In the current study, we measured looking times and ERPs to systematically examine the cognitive and cortical mechanisms of object perceptual categorization in 6-month-old infants. Specifically, we asked (a) whether different neural signatures accompany basic-level perceptual category and exemplar distinctions in young infants, and (b) whether infants engage different brain processes when they make basic-level distinctions within or across taxonomic global-level boundaries.

At the neural level, studies with monkeys (Freedman, Riesenhuber, Poggio, & Miller, 2001, 2003) have provided support for a model of category learning in which neuronal populations in extrastriate visual cortex come to acquire higher degrees (sharper tuning) of selectivity for trained exemplars of stimuli within a category—a mechanism also hypothesized to underlie many developmental changes in infant categorization (Westermann & Mareschal, 2004). These exemplar-selective neurons

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the prior preference, the categorization and identification tests. Paired *t* tests were used to compare looking time differences between conditions statistically.

### ERP Procedure

The infants sat on their parent's lap at a 60-cm distance from a 19-in. computer monitor within an acoustically and electrically shielded and dimly lit room. A video camera mounted below the monitor and centered on the infants' face allowed us to record their looking behavior. The experimental procedure in the ERP study was as closely matched to the behavioral study as possible. All object stimuli were presented for 1 sec followed by a randomly varying (500–700 msec) interstimulus interval during which a fixation stimulus (flower) accompanied by various sounds effects was presented. As in the behavioral study, during the familiarization phase, we presented infants with 40 trials (images) from one category in pseudo-randomized order (4 images were repeated during the familiarization 5 times). After the familiarization, infants watched three kinds of test trials: four familiar category-repeated images (which had been presented five times during familiarization), four familiar category-new images (not presented during familiarization), and eight new category images. Images were presented in a pseudorandomized order with no more than two images from the same category presented in succession. Infants typically completed between 120 and 150 trials (including familiarization) before the session was concluded.

### EEG Recording and Data Analysis

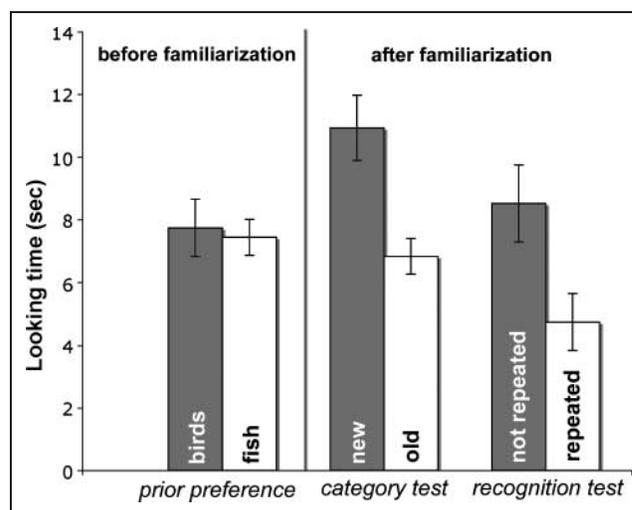
The brain's electric activity was measured with the infant version of the Geodesic Sensor Net (64 Channel V2.0). The reference electrode was the vertex (Cz in the conventional 10–20 system). The electrical potential was amplified with 0.1–100 Hz band pass, digitized at 250 Hz sampling rate, and stored on computer disk for the off-line analysis. The behavior of all participants was initially coded from videotape so that only those trials in which the infants were fixating the center of the screen during the trial, without blinking or eye or head movements, were included in the analysis of electrophysiological signals. Data from each sensor were removed if they contained artifacts created by movement or poor contact. The entire trial was excluded if data from more than 10 sensors had been removed or if the trial contained an eye blink or other artifact. Missing data for trials with 10 or fewer bad channels were interpolated using spherical spline interpolation. Data were re-referenced to average reference, baseline-corrected, and then individual participant averages were computed for each trial type. Infants with less than 10 artifact-free trials in the familiarization conditions, or less than 15 artifact-free trials in any of the test conditions, were excluded. The average number of trials was: (1) during familiarization: repeated

trials  $M = 14.5$  ( $SD = 4.0$ ), not repeated trials  $M = 15.8$  ( $SD = 3.7$ ); (2) during test: familiar category trials  $M = 21.4$  ( $SD = 5.7$ ), new category trials  $M = 23.1$  ( $SD = 6.2$ ). Average ERPs were obtained time-locked to the onset of the object stimulus, ERP amplitude was assessed by averaging the data within two regions of interest (anterior channels [3, 4, 5, 8, 9, 13, 17, 18, 30, 43, 54, 55, 58, 62]: electrodes over frontal cortex; posterior channels [32, 33, 34, 37, 38, 39, 40, 41, 45]: electrodes over occipito-posterior temporal cortex) (see Figures 3, 4, 6, and 7) for three consecutive time windows (100–300 msec, 300–500 msec, 500–1000 msec). These regions of interest and time windows were chosen on the basis of previous studies (Carver et al., 2006; Quinn et al., 2006) and the visual inspection of the data. Repeated measures ANOVAs with the within-subjects factors region (anterior, posterior) and condition (for within-category contrast: repeated, not repeated; for between-category contrast: new items new category, new items familiar category) were conducted to examine the ERP effects statistically. These ANOVAs were performed on transformed (vector scaled) data according to McCarthy and Woods (1985). Planned comparisons (within category and between category) were conducted for posterior and anterior regions separately using paired-sample *t* tests.

## Results

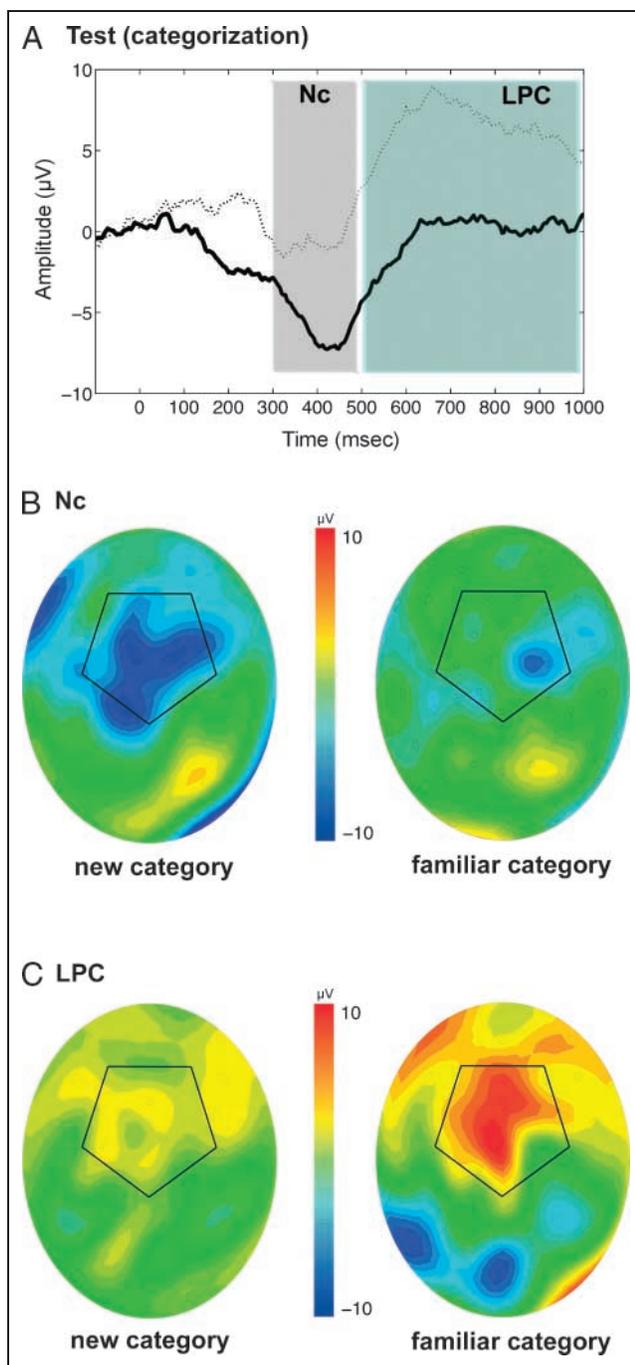
### Study 1: Basic-level Categorization within a Single Global Category (Birds vs. Fish)

**Behavioral results.** An overview of the behavioral results in Study 1 is shown in Figure 2. Our analysis revealed that before familiarization, infants had no prior preference for birds over fish images [ $t(11) = 0.56, p = .59$ ]. After familiarization to images of one category, infants showed a preference for images from the novel



**Figure 2.** Overview of behavioral looking time results for the prior preference, category, and visual recognition tests of Study 1.





**Figure 4.** This graph depicts the ERPs measured in Study 1 at anterior channels during test (top) in response to new items from the new category (solid line) and new items from the familiar category (dotted line) and the scalp topography of the ERPs (right). Selected channels used for calculating the ERPs on the left were within the region marked on the scalp topography map by the black frame. The time windows (Nc: 300–500 msec; LPC: 500–1000 msec) during which statistically significant differences between conditions were found are marked in gray and green, respectively. Nc scalp topography is an average for a time window from 360 to 440 msec. LPC scalp topography is an average for a time window from 640 to 720 msec.

that images of the familiar category when compared to the new category evoked an enhanced late positive component (LPC, 500–1000 msec), whereas images from the new category resulted in a potential that returned to baseline [ $t(13) = 3.14, p = .008$ ]. The LPC was also found to be greater in amplitude when the new items of the familiar category were compared to the repeated items of the familiar category [ $t(13) = 2.47, p = .028$ ]. No such effects were obtained at posterior channels. There were no significant differences between the groups of infants that were familiarized to birds versus fish.

## Discussion

In Study 1, we showed that repeating individual exemplars resulted in differential cortical processing at posterior channels at an early stage during object processing, whereas discriminating among members of different categories was reflected in ERP differences over anterior cortical regions occurring later in time than the repetition effects of individual exemplars. More specifically, the anterior component (Nc) did not differ between new and familiar instances of the familiar category, but was enhanced for new items of the unfamiliar category, providing ERP evidence that infants have categorized. This pattern of findings including the timing and the topography of the effects is in line with previous ERP work on perceptual category learning in adults (Scott et al., 2006, 2008; Tanaka et al., 1999), and it critically extends the one previous infant ERP study on this topic (Quinn et al., 2006).

The timing of the ERP responses reported in this study with an earlier component for within-category discrimination and a later component for categorization in infants seem to be inconsistent with behavioral findings in adults showing faster categorization relative to object identification (Grill-Spector & Kanwisher, 2005). However, this difference might be explained by the fact that adults were explicitly instructed to specifically identify objects on the basis of linguistic subordinate labels, whereas infants in the current study had to simply detect the items that were repeated.

The repetition of exemplars within a category evoked an increase in amplitude during the learning (familiarization) phase and a decrease in amplitude during the test phase over the same posterior regions. Amplitude changes with repetition of a visual stimulus have been measured at the level of individual neurons in macaques (Desimone, 1996) and with brain imaging methods in human adults (for a review, see Grill-Spector, Henson, & Marin, 2006). Similar repetition effects have been observed in young infants for posterior ERP components (N290 and P400) in response to face stimuli (Gliga & Dehaene-Lambertz, 2007). The familiarity of the stimuli affects the direction of the repetition effects: An increase in response occurs for unfamiliar stimuli and a decrease with the repetition of familiar stimuli (Henson, Shallice,

& Dolan, 2000). These dynamics are believed to correspond to an initial learning period when a representation of stimulus is created and more perceptual information is incorporated to represent an object (the response enhancement), followed by an adaptation of the response once a more robust object representation is formed (the response suppression). The current ERP findings with infants reveal a very similar pattern of repetition enhancement and suppression depending on the familiarity of an object, suggesting that similar perceptual learning mechanisms as found in adults might be at work already early in human development. However, our design did not allow us to examine exactly how much experience (how many repetitions) is required to form a robust exemplar representation. Thus, studying repetition effects during infancy and correlating them with behavioral discrimination measures in future studies will provide important insights into the neural mechanisms and development of perceptual learning.

## STUDY 2

In Study 2, we presented 6-month-old infants with either bird or car images during the learning phase (familiarization), crossing categories at a global level (animals vs. vehicles), and then tested them with novel images from the familiar and unfamiliar categories. As in Study 1, we presented four images during the familiarization repeatedly, which were then repeated during test to assess infants' visual recognition (see Figure 1). We examined both behavioral (Study 2a) and ERP measures (Study 2b) in two separate groups of infants. On the basis of perceptual accounts of infant category learning (Quinn & Eimas, 1996, 2000), we hypothesized that infants at this age utilize similar cortical processes to categorize visual objects regardless of the level at which a category boundary is crossed (Study 1: basic-level within a single global level, or Study 2: basic-level across two global levels). Therefore, we predicted that Study 2 would replicate the effects found in Study 1.

## Methods

### Participants

*Studies 2a and 2b.* Seventeen infants participated in the behavioral experiment of Study 2a. The final sample consisted of 16 infants (9 girls), aged between 166 and 194 days ( $M = 181$  days). One infant was excluded because of completing too few trials. Twenty-five infants participated in the ERP experiment of Study 2b. The final sample consisted of 14 infants (7 girls), aged between 170 and 192 days ( $M = 178$  days). The remaining 11 were excluded because of excessive artifacts or completing too few trials.

## Stimuli

The stimuli were digitized color photographs of visual objects from two different categories (birds and cars) (see Figure 1). The creation of the stimuli was otherwise kept identical to Study 1.

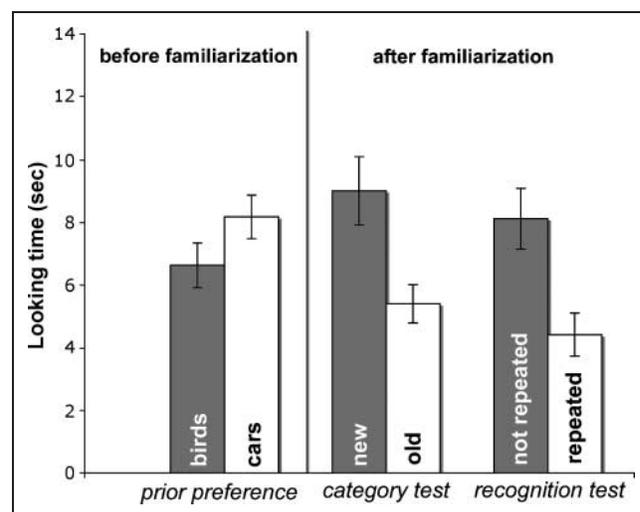
## Behavioral Procedure and Data Analysis, ERP Procedure, and EEG Recording and Data Analysis

All these aspects of Study 2 were kept identical to Study 1. The average number of trials was: (1) during familiarization: repeated trials  $M = 13.2$  ( $SD = 3.3$ ), not repeated trials  $M = 14.1$  ( $SD = 4.1$ ); (2) during test: familiar category trials  $M = 22.7$  ( $SD = 3.9$ ), new category trials  $M = 24.3$  ( $SD = 4.8$ ).

## Results

### Study 2: Basic-level Categorization across Two Global Categories (Birds vs. Cars)

*Behavioral results.* An overview of the behavioral results in Study 2 is shown in Figure 5. Our analysis revealed that before familiarization infants had no prior preference for cars over birds [ $t(15) = 1.85, p = .09$ ]. After familiarization to images of one category, infants showed a preference for images from the novel category, that is, they looked significantly longer at images from the new category when compared to new images from the familiar category [ $t(15) = 3.50, p = .003$ ]. The difference in looking time post familiarization was significantly greater than the difference in looking time in the prior preference test [ $t(15) = 2.74, p = .015$ ]. A significant novelty preference (longer looking) was also found for new (not repeated) images over repeated images from the familiar category [ $t(15) = 5.97, p < .001$ ].

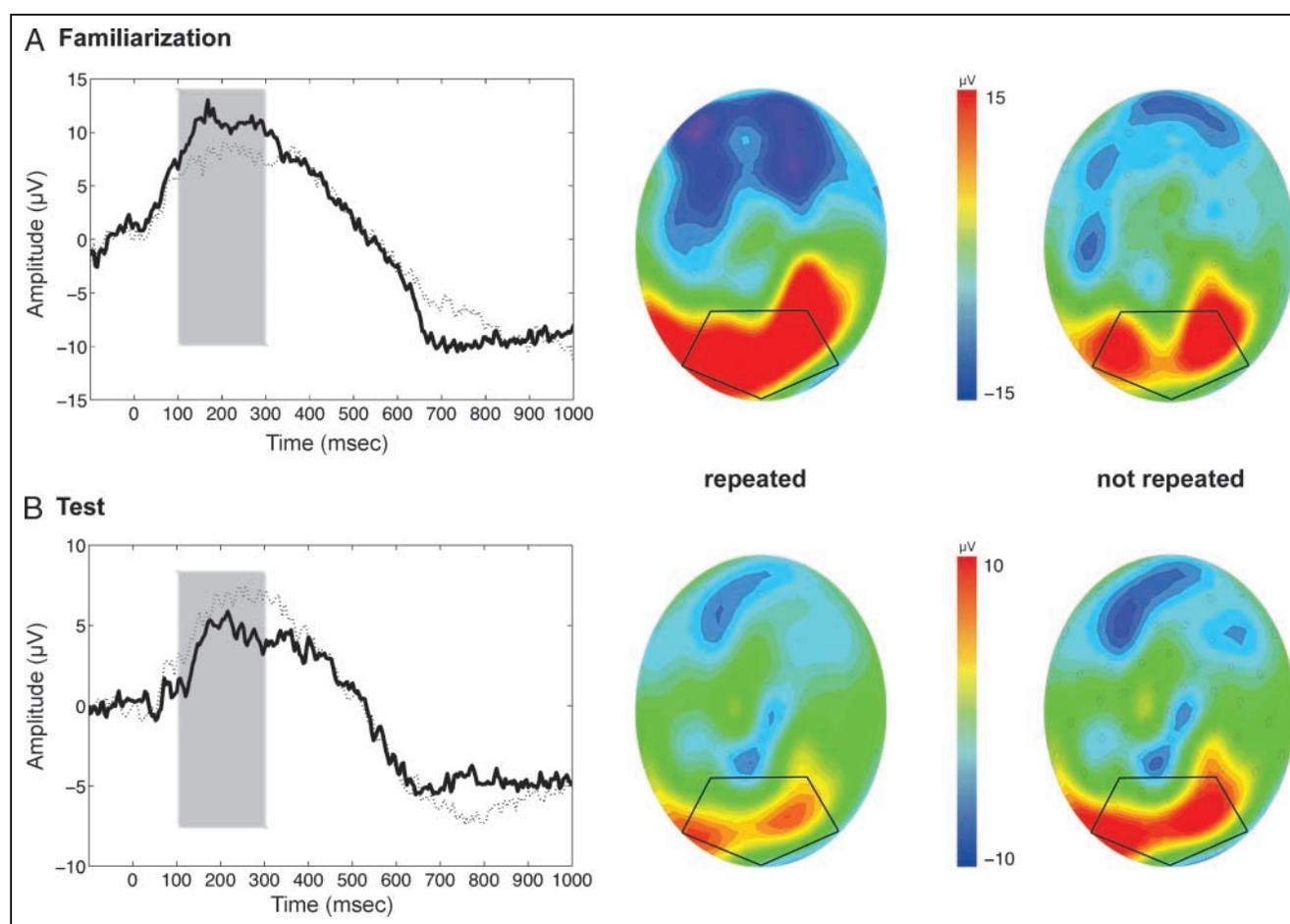


**Figure 5.** Overview of behavioral looking time results for the prior preference, category, and visual recognition tests of Study 2.

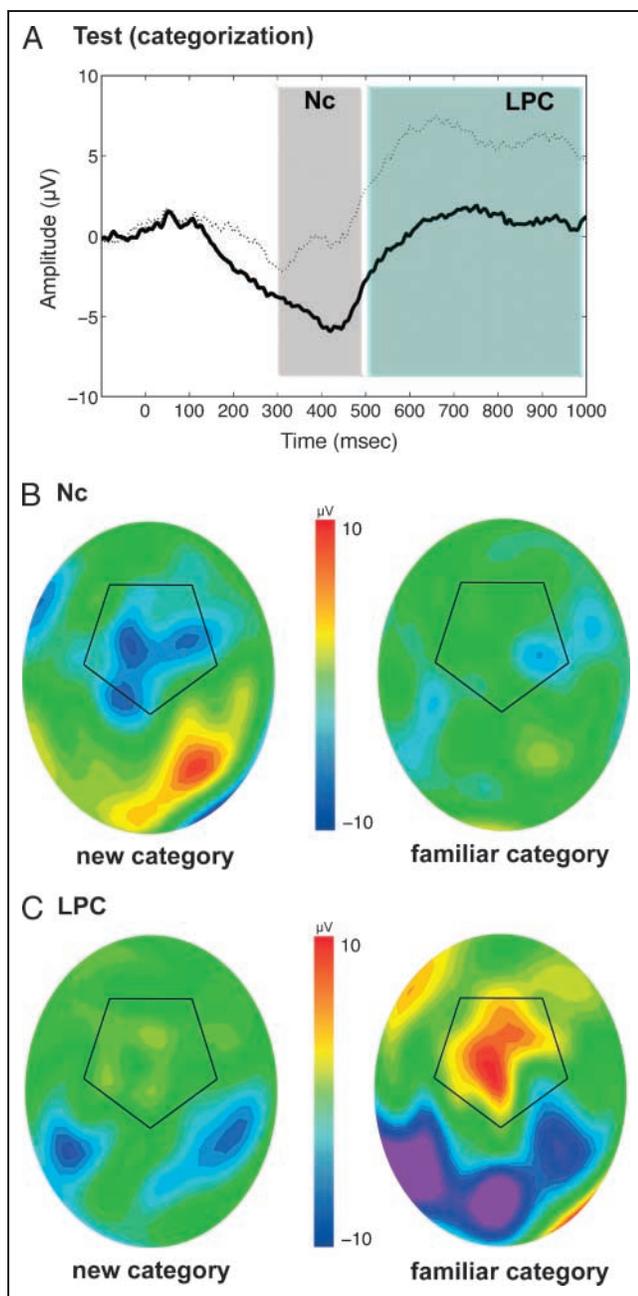
There were no significant differences between the groups of infants that were familiarized to birds versus cars.

**ERP results (within-category contrast).** Our analysis revealed a two-way interaction between region (anterior, posterior) and condition (repeated, not repeated) during the familiarization [ $F(1, 13) = 7.13, p = .019$ ] and during the test [ $F(1, 13) = 6.25, p = .026$ ] for the within-category comparison. As shown in Figure 6, during familiarization, repeated images when compared to nonrepeated images elicited an enhanced early positive component (100–300 msec) at posterior channels [ $t(13) = 2.57, p = .023$ ]. During test, this effect was reversed, that is, repeated images elicited an early positive component (100–300 msec) that was suppressed in its amplitude when compared to the nonrepeated images [ $t(13) = 2.83, p = .014$ ]. No such effects were obtained at anterior channels. There were no significant differences between the groups of infants that were familiarized to birds versus cars.

**ERP results (between-category contrast).** Our analysis revealed a two-way interaction between region (anterior, posterior) and condition (new items familiar category, new items new category) for the between-category comparison during test [ $F(1, 13) = 11.51, p = .004$ ]. As shown in Figure 7, at anterior channels, images of the new category compared to images of the familiar category elicited a mid-latency Nc (300–500 msec) that was enhanced in its amplitude [ $t(13) = 3.38, p = .005$ ]. In addition, the results revealed that images of the familiar category when compared to the new category evoked an enhanced LPC (500–1000 msec), whereas images from the new category resulted in a potential that returned to baseline [ $t(13) = 2.93, p = .012$ ]. The LPC was also found to be greater in amplitude when the new items of the familiar category were compared to the repeated items of the familiar category [ $t(13) = 2.25, p = .042$ ]. No such effects were obtained at posterior channels. There were no significant differences between the groups of infants that were familiarized to birds versus cars.



**Figure 6.** This graph depicts the ERPs measured in Study 2 at posterior channels during familiarization and test (left) in response to repeated items (solid line) and not repeated items (dotted line) and the scalp topography of the ERPs (right). Selected channels used for calculating the ERPs on the left were within the region marked by the black frame. The time window (100–300 msec) during which statistically significant differences between conditions were found is marked in gray. The scalp topography is presented for a time window from 160 to 240 msec.



**Figure 7.** This graph depicts the ERPs measured in Study 2 at anterior channels during test (top) in response to new items from the new category (solid line) and new items from the familiar category (dotted line) and the scalp topography of the ERPs (right). Selected channels used for calculating the ERPs on the left were within the region marked on the scalp topography map by the black frame. The time windows (Nc: 300–500 msec; LPC: 500–1000 msec) during which statistically significant differences between conditions were found are marked in gray and green, respectively. Nc scalp topography is an average for a time window from 360 to 440 msec. LPC scalp topography is an average for a time window from 640 to 720 msec.

*Comparison of ERP findings of Study 1 and Study 2.* In order to compare statistically the pattern of ERP findings between Study 1 and Study 2, we calculated (1) the ERP amplitude differences between the experimental con-

ditions, and (2) the peak latency of this difference for each infant. For these two dependent measures, we then conducted repeated measures ANOVAs with between-subjects factor study (two levels: Study 1, Study 2) and within-subjects factor ERP effect (four levels: familiarization posterior channels, test posterior channels, test anterior channels Nc, test anterior LPC). This analysis revealed no main effect of the factor study [ERP amplitude:  $F(1, 26) = 0.35, p = .559, \eta_p^2 = 0.079$ ; peak latency:  $F(1, 26) = 0.18, p = .675, \eta_p^2 = 0.063$ ] and no interaction between the factors study and ERP effect [ERP amplitude:  $F(3, 78) = 0.19, p = .903, \eta_p^2 = 0.017$ ; peak latency:  $F(3, 78) = 0.32, p = .811, \eta_p^2 = 0.038$ ] for either of the dependent measures (ERP amplitude difference and peak latency), indicating that there were no significant differences in the ERP findings across studies.

## Discussion

In Study 2, we contrasted basic-level categories (birds and cars) that crossed a taxonomic global-level boundary (animals and vehicles) and replicated the behavioral and ERP effects reported in Study 1, indicating that perceptual categorization processes can be reliably elicited in these young infants. As predicted, there were no differences in the brain processes that 6-month-old infants engage when they discriminate between basic-level categories within (Study 1) or across the global-level (Study 2) of an abstract hierarchy. This suggests that, in our study, infants do not employ any additional or different brain processes when they tease apart basic-level perceptual categories that belong to different global-level categories (i.e., animals and vehicles). Finally, in the current study, this distinction was assessed by contrasting two basic-level perceptual categories instead of two global-level categories consisting of various basic-level exemplars (animals: fish, birds, horse, etc.) because using global-level categories would have introduced additional perceptual variance across categories, thereby introducing a confound between perceptual variability and level of categorization in any comparison of the ERP effects across Study 1 and Study 2 (see Thierry, Martin, Downing, & Pegna, 2007).

## GENERAL DISCUSSION

ERPs measured in 6-month-olds in a perceptual category learning paradigm revealed that (a) perceptual categorization and exemplar discrimination rely on cortical processes that are distinct in timing and spatial distribution and (b) that at this age, infants utilize similar cortical processes to categorize visual objects at the basic level regardless of whether the distinction is within or across taxonomic global-level domains.

Previous work with human adults and monkeys has revealed category-based representations in prefrontal cortex

(see Freedman & Miller, 2008 for a review). Similarly, we found that in 6-month-olds an ERP component (Nc) over anterior cortical regions was sensitive to category information. In prior work, the cortical sources of this infant ERP component have been localized in prefrontal cortex (including inferior, medial and superior frontal gyri, and anterior cingulate cortex; see Reynolds & Richards, 2005). The similarity between the adult and monkey findings and the current data seems striking but one has to be careful in interpreting this similarity as different methods were used across studies. Furthermore, the infant Nc component is associated with a wide range of attention-recruiting tasks (Csibra, Kushnerenko, & Grossmann, 2008) and may therefore not be a category-specific response per se but could rather be interpreted in terms of increased attention allocation toward the out-of-category exemplar. However, this would not undermine the fact that only the out-of-category exemplars, not the new exemplars of the familiar category, grabbed the infants' attention, as reflected in the specific modulation of this ERP component.

Following the Nc, we observed an LPC in response to new items of the familiar category, whereas items of the new category resulted in a return to baseline. This infant ERP component is thought to be involved in the updating of an existing memory representation (Nelson & Collins, 1991; see also Nelson, Thomas, de Haan, & Wewerka, 1998; Nelson, 1994, for discussion of the response properties of this component) and might thus reflect processes related to the integration of new exemplars into an already existing representation (possibly prototype) of the familiar category. This interpretation is also consistent with (a) the finding that novel exemplars of the familiar category elicited a larger LPC than repeated exemplars of the familiar category, and (b) the notion that this component might be an index of category learning as suggested by Quinn et al. (2006). It is interesting to note that although the LPC occurred later in the ERP than the Nc, both components showed a very similar scalp topography, which might indicate that out-of-category detection and updating of category representations relies on similar brain processes but differs with respect to its timing.

Another line of work that might help to interpret our current findings has compared implicit to explicit category learning in adults using fMRI. Reber, Gitelman, Parrish, and Mesulam (2003) observed decreased occipital activity for novel categorical stimuli compared with noncategorical stimuli following implicit learning. In contrast, after explicit (instructed) learning, novel categorical stimuli evoked increased activity in prefrontal cortex (and some other regions), suggesting that category knowledge depends on how it is learned. This pattern of findings in adults may suggest that infants, who showed a category-sensitive component over anterior brain regions in the current study, are actively engaged in organizing the stimuli they were presented with into categories.

Another important finding of our study was that, for both behavioral and ERP measures, it did not seem to matter whether the basic-level categories contrasted crossed a global-level divide or not. Birds were considered as far apart from fish as they were from cars, as suggested by the similar Nc responses evoked by the new category exemplars in Study 1 and Study 2. This is consistent with perceptual account of early infant categorization, at least at the age we have tested (Quinn & Eimas, 1996, 2000; Quinn, Johnson, Mareschal, Rakinson, & Younger, 2000). In future work, the paradigm developed in this study could be used to (a) examine older infants who are known to have acquired conceptual category knowledge to see how this affects the brain processes involved in object categorization (see Mandler, 2004), and (b) to assess global-level categorization directly by contrasting, for example, animals (fish, birds, etc.) and vehicles (cars, boats, etc.).

In summary, the current study provided important insights into the brain dynamics of perceptual learning and categorization in infancy. It further provided developmental support for an existing neural-level model of perceptual categorization that was thus far based on neuroimaging work with adults and monkeys (Freedman & Miller, 2008; Scott et al., 2006, 2008; Tanaka et al., 1999). Thus, this study demonstrates how cognitive neuroscience and developmental cognitive psychology can cross-fertilize each other and thereby contribute to the progress in the new field of developmental cognitive neuroscience (Johnson, 2005).

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