



PAPER

Neural markers of subordinate-level categorization in 6- to 7-month-old infants

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Abstract

Subordinate-level category-learning processes in infants were investigated with ERP and looking-time measures. ERPs were recorded while 6- to 7-month-olds were presented with Saint Bernard images during familiarization, followed by novel Saint Bernards interspersed with Beagles during test. In addition, infant looking times were measured during a paired-preference test (novel Saint Bernard vs. novel Beagle) conducted at the conclusion of ERP recording. Slow wave activity corresponded with learning a familiarized category at the subordinate and basic levels, whereas Negative central (Nc) and P400 components were linked with novel category preference. The results provide the first evidence identifying the neural markers of subordinate-level categorization observed in looking-time tasks conducted with infants. Moreover, when considered in conjunction with prior research investigating the neural markers of basic-level categorization in infants, the findings indicate that (1) slow wave and Nc components of infant ERP waveforms are general markers for processes of category learning on the one hand and novel category preference on the other, (2) novel category preference for a contrast category at the basic and subordinate levels have the Nc component in common, but novel category preference at the subordinate level is accompanied by an additional P400 component, a finding in keeping with the notion that subordinate-level categorization is governed by mechanisms supplementary to those underlying basic-level categorization, and (3) slow wave activity associated with subordinate-level learning followed that associated with basic-level learning by approximately 200 ms, a result in accord with a coarse-to-fine scheme for the emergence of category partitioning.

Introduction

The ability to parse experience into coherent categories is believed to be essential for successful adaptation to the environment (Murphy, 2002). Understanding the origins and development of this ability has become a major research endeavor for many concerned with cognitive development (e.g. Carey, 2000; Mandler, 2000). Looking-time studies measuring the emergence of categorization during early development have provided evidence that young infants can categorize visual information based on perceptual experience (Mareschal & Quinn, 2001). With a familiarization/novelty-preference methodology, infants are presented with multiple instances from a common category during familiarization and then with a preference test pairing a novel instance from the familiar category with a novel instance from a novel category. Categorization is inferred if infants generalize familiarization to the novel instance from the familiar category and display a preference for the novel instance from the novel category.

Looking-time studies conducted with this familiarization/novelty-preference methodology have produced

evidence for a differentiation-driven trend from broad to narrow representations over the first 6 to 7 months. For example, 2-month-olds have been shown to form a global (superordinate) category representation for mammals that excludes furniture, but not a basic-level category representation for cats that excludes rabbits or dogs (Quinn & Johnson, 2000). At 3 to 4 months, infants show evidence of forming both a global category representation for mammals that excludes furniture, and a basic-level category representation for cats that excludes horses and dogs (Behl-Chadha, 1996; Eimas & Quinn, 1994; Quinn, Eimas & Rosenkrantz, 1993). However, these infants fail to show evidence of forming a subordinate-level representation for Tabby cats that excludes Siamese cats, or Saint Bernard dogs that excludes Beagle dogs (Quinn, 2004). Finally, 6- to 7-month-olds have been shown to form a basic-level representation for cats that excludes tigers and lions (Eimas & Quinn, 1994), and subordinate-level representations for Tabbies that exclude Siamese and Saint Bernards that exclude Beagles (Quinn, 2004; Quinn & Tanaka, 2007). The global-to-basic-to-subordinate developmental trend in infant category learning is noteworthy because it contrasts with the

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traditional basic-to-superordinate account of category learning in children (Rosch, Mervis, Gray, Johnson & Boyes-Braem, 1976), although the finding that the subordinate level is the last to emerge is consistent with investigations of the acquisition of subordinate-level expertise in adults (e.g. Gauthier & Tarr, 1997; Tanaka, 2001).

Studies of category learning of animals by infants have implications for theories of semantic cognition because they suggest that young infants divide the world of objects into perceptual groupings that come to have conceptual meaning for children and adults (Rogers & McClelland, 2004). That is, the conceptual representations found later in development can be viewed as informational enhancements of the category representations that infants form on the basis of perceptual experience (Quinn & Eimas, 1997). The perceptual category representations, on this view, serve as placeholders for the acquisition of the more abstract information that occurs beyond infancy (i.e. cats give birth to kittens and have cat DNA) through language and learning of the non-obvious attributes that become linked with semantic categories (Quinn & Eimas, 2000). By this account, what changes as concepts mature is the content of the representations, rather than the mechanisms underlying their development (Madole & Oakes, 1999; Rakison & Poulin-Dubois, 2001).

At the same time that a body of research has been emerging on category formation by infants, another literature has been emerging on the neural basis of object recognition and categorization in adults (Tanaka, 2004). Like the infant categorization work, the adult cognitive neuroscience literature indicates that categorization performance depends critically on the level of category exposure. Functional magnetic resonance imaging (fMRI) and event-related brain potential (ERP) investigations suggest that different brain regions sort objects into specific category levels and that early and later components of brain waves are differentially sensitive to different category levels (Gauthier, Skudlarski, Gore & Anderson, 2000; Tanaka, Luu, Weisbrod & Kiefer, 1999). For example, ERP studies have shown that while both basic- and subordinate-level categorizations result in an enhanced N170, only subordinate-level categorizations elicit an enhanced N250 (Scott, Tanaka, Sheinberg & Curran, 2006).

In addition, since the work of Miller and colleagues (Freedman, Riesenhuber, Poggio & Miller, 2001), it has been believed that category learning at the basic level may be coded in single cells of the brain. For example, individual neurons in the dorsolateral prefrontal cortex in awake, behaving monkeys trained to categorize images of cats and dogs became selective for one or the other basic-level category. Subordinate-level categorization may also have a neural analogue at the single-cell level (Sigala & Logothetis, 2002). As a consequence of categorization training designed to teach monkeys to differentiate between classes of outline face or fish stimuli, individual neurons in the inferotemporal cortex

of the monkeys became preferentially responsive to features that were diagnostic of the category contrast relative to other features that were present in the stimuli, but not categorically distinguishing. The operation of such 'expert neurons' suggests a neural correlate of expertise at the single-cell level in a part of the brain that has been associated with object recognition (Hasegawa & Miyashita, 2002; but see Thomas, Van Hulle & Vogels, 2001; see also Ashby & Spiering, 2004).

In an initial effort to bridge the infant categorization and adult cognitive neuroscience literatures, Quinn, Westerlund and Nelson (2006) used an ERP analogue of the behavioral looking-time procedure to explore the neural correlates of category formation by infants. Six- to 7-month-olds were familiarized with 36 cat images followed by test trials consisting of 20 novel cat images interspersed with 20 novel dog images. The results were partitioned into four different conditions: cats 1–18, cats 19–36, novel cats, and novel dogs. Evidence for learning a familiarized category at the basic level (i.e. cat) was manifest in a late slow wave component. In particular, a Negative Slow Wave (NSW) was observed over left occipital-parietal scalp in response to cats 1–18 and novel dogs (reflecting initial experience with exemplars of a category), whereas a slow wave that returned to baseline was observed for cats 19–36 and novel cats (reflecting a learned category of cats). These findings correspond well with studies of recognition memory for individual stimuli in infants (Nelson, 1994; Reynolds & Richards, 2005), where the amplitude of the slow wave has been associated with differentiation of familiar and novel stimuli. In particular, a slow wave that returns to baseline has been associated with recognition of familiarity, whereas a slow wave that deflects away from baseline in either a positive or negative direction has been associated with detection of novelty.

Evidence for learning a familiarized category at the global (superordinate) level (i.e. cat + dog) was manifest in a Positive Slow Wave (PSW) over right frontal scalp for cats 1–18 (reflecting initial experience with exemplars of a category), whereas a slow wave that returned to baseline was observed for cats 19–36, novel cats, and novel dogs (reflecting a learned representation of cat + dog). Notably, the global-level differentiation (separation of cats 1–18 from cats 19–36, novel cats, and novel dogs) began approximately 200 ms before the basic-level contrast (separation of cats 19–36 and novel cats from cats 1–18 and novel dogs). This sequential emergence of the global and basic levels is consistent with the behavioral evidence that category learning in the domain of objects proceeds from broad to narrow.

In addition to observing brain-based evidence for category learning at basic and global levels, Quinn *et al.* (2006) also reported an ERP component for preferring a novel contrast category. Specifically, a Negative central (Nc) component which has been linked with attentional responding to novelty in studies of recognition memory (Reynolds & Richards, 2005) was larger over left central

scalp for novel dogs relative to cats 1–18, cats 19–36, and novel cats. Grossmann, Gliga, Johnson and Mareschal (in press) also reported enhanced Nc activity for novel category instances over novel instances from a familiarized category in a more recent study of the ERP signals associated with basic-level category learning in infants (e.g. birds vs. fish vs. cars).

The present study extends the Quinn *et al.* (2006) findings by investigating the neural mechanisms of subordinate-level category learning in infants. Using the familiarization/novelty-preference procedure, ERPs were recorded with a Geodesic Sensor Net composed of 64 electrodes (Tucker, 1993) while 6- to 7-month-olds were familiarized with 36 Saint Bernard images, followed by test trials comprising 20 novel Saint Bernards interspersed with 20 Beagles. At the conclusion of ERP recording, infant looking times were measured during a paired-preference test (novel Saint Bernard vs. novel Beagle).¹

By measuring the ERP markers of infant categorization at the subordinate level with the same methodology that was used by Quinn *et al.* (2006) to measure infant categorization at the basic level, the current research can determine whether category learning and novel category preference will again be manifested in slow wave activity and in the Nc component, respectively. This issue is important to investigate because it will allow one to determine whether the slow wave and Nc components may be regarded as general markers for category learning and novel category preference, rather than idiosyncratic responses to a particular category contrast. In addition, the current research can determine whether, as is the case in adults (Scott *et al.*, 2006), category learning at the subordinate level is marked by the activity of additional components not observed at the basic level. Also, by examining the relative timing relation between the slow wave components associated with learning at different

category levels (subordinate and basic), the present study may provide further support for the broad-to-narrow trajectory of category learning.

Method

Participants

The participants were 10 healthy, full-term 6- to 7-month-olds (six females) with a mean age of 186.80 days ($SD = 9.59$ days). This sample size matches with that of Quinn *et al.* (2006). Eighteen additional infants were tested, but six failed to complete the procedure due to fussiness, and 12 were excluded from the data analysis due to movement artifacts ($n = 11$) or experimenter error ($n = 1$). None of the infants were reared in a household in which there was a pet dog. Participants were predominantly Caucasian and from middle-class backgrounds.

Stimuli

Stimuli were colored photographs of Saint Bernards and Beagles and were cut from the same pet books and animal field guides as the stimuli used in Quinn (2004) and Quinn and Tanaka (2007).^{2,3} They were chosen to represent a variety of stances and orientations, and selected to be as nearly the same size as possible. Each

² In addition to the 18 Saint Bernard stimuli and the 18 Beagle stimuli that were used in the Quinn (2004) and Quinn and Tanaka (2007) studies, the current investigation employed a further 39 Saint Bernard stimuli and three Beagle stimuli. To assess the within-category discriminability of these stimuli, 32 additional 6- to 7-month-olds (Mean Age = 192.33 days, $SD = 10.95$, 14 females) were presented with a Saint Bernard ($n = 24$) or Beagle ($n = 8$) for a single 15-s familiarization trial and then tested with the familiar stimulus paired with a novel exemplar from the same subordinate-level category on two 10-s preference test trials. The familiar and novel instances from each category were randomly selected for each infant. Infants in the Saint Bernard condition looked for an average of 8.54 s ($SD = 3.06$) and displayed an above-chance mean novelty preference of 61.12% ($SD = 15.34$), $t(23) = 3.55$, $p < .01$. Likewise, infants in the Beagle condition looked for an average of 8.98 s ($SD = 3.59$) and displayed an above-chance mean novelty preference of 58.16% ($SD = 8.49$), $t(7) = 2.72$, $p < .05$. These results indicate that, like the original stimuli used in the earlier behavioral studies (Quinn, 2004; Quinn & Tanaka, 2007), the additional stimuli used in the current study were also discriminable for the infants on a within-category basis.

³ Although the prior behavioral studies (Quinn, 2004; Quinn & Tanaka, 2007) had indicated that there was no spontaneous preference for Beagles versus Saint Bernards, given the larger stimulus sets used in the current study, we again measured for spontaneous preference by presenting an independent group of 6- to 7-month-olds ($n = 24$, Mean Age = 191.54 days, $SD = 7.78$, 13 females) with different, randomly selected pairs of pictures from the two different categories on each of eight 10-s trials (i.e. Beagle vs. Saint Bernard). The mean preference for the Beagles was 50.27% ($SD = 12.07$), a value that was not different from chance, $t(23) = 0.11$, $p > .20$, thereby indicating that any differential response to the Beagles versus Saint Bernards was not due to an intrinsic salience difference between the categories.

¹ We conducted the ERP study in only a single direction because the original behavioral results from Quinn (2004) showed that positive evidence for categorization was obtained only when the infants were familiarized with Saint Bernards and tested with Beagles. It follows that one would not look for neural markers of categorization in an ERP task for a category contrast that yielded null results on a looking-time task (i.e. familiarization with Beagles and test with Saint Bernards). In a subsequent behavioral study, Quinn and Tanaka (2007) provided positive evidence for categorization when infants were familiarized with Beagles and tested with Saint Bernards, but only in a two-part categorization procedure in which infants were initially familiarized with Saint Bernards and tested with Beagles. Such behavioral evidence is consistent with Tanaka, Curran and Sheinberg's (2005) work with adults showing that experience with subordinate-level categorization of objects from within a basic-level category may tune one's perceptual system to features that are diagnostic for subordinate-level contrasts within that basic-level category. Examining the ERP correlates of such perceptual tuning in infants could in principle be a very informative investigation. However, practically, it would require infants to sit through double the number of trials of the current investigation, a design feature that we did not view as feasible.

picture contained a single animal that had been cut away from its background. Average luminosity was measured for each image in Adobe Photoshop and ranged from 201.38 to 243.65 for Saint Bernards ($M = 222.30$) and from 200.13 to 239.40 for Beagles ($M = 220.01$). In addition, standard deviation of luminosity values within each image was measured and ranged from 39.91 to 81.52 for Saint Bernards ($M = 62.95$) and from 44.77 to 85.68 for Beagles ($M = 63.34$). Area and perimeter were also measured in centimeters with a LASICO 1281 Area/Line Meter and used to derive a shape estimate ($\text{perimeter}^2/\text{area}$) for each image (Zusne, 1970). Shape values ranged from 24.93 to 51.84 for Saint Bernards ($M = 42.77$) and from 23.61 to 56.46 for Beagles ($M = 44.30$). None of the mean differences between breeds were significant. These measures help to ensure that the results of the experiment reflect responding to category differences between Saint Bernards and Beagles rather than spurious differences between two image sets.

Procedure

ERP testing

Infants sat on their parent's lap 60 cm away from an UltraScan P990 19-inch CRT monitor (48 cm × 31 cm; 1024 × 768 pixel resolution; 75-Hz frame rate) within an electrically shielded and dimly-lit room. A video camera mounted above the monitor and centered on the infant's face allowed for recording of gaze. Each stimulus consisted of a single animal that was centered on the monitor and presented for 500 ms. The 36 familiar Saint Bernards, 20 novel Saint Bernards, and 20 novel Beagles were randomly selected for each infant. Order of presentation of the familiar Saint Bernards, and the intermingled presentation of novel Saint Bernards and novel Beagles, was also randomly determined for each infant. Using the image from the video camera, online judgments were employed to present pictures only when the infant was attending to the monitor. During electrophysiological recording, an experimenter sat beside the infant to redirect his or her attention to the stimuli if the infant became distracted.

ERP waveform analysis

The electroencephalogram (EEG) was recorded with a vertex reference, amplified with 0.1- to 100-Hz band-pass filtering, digitized at a 250-Hz sampling rate, and stored in real time on a computer. EEG data were then processed offline using NetStation 4.1.2 (Electrical Geodesics, Inc., Eugene, OR), beginning with a 30-Hz low-pass filter followed by data segmentation time-locked to stimulus onset with 100-ms prestimulus and 1500-ms poststimulus durations. Data were subsequently baseline corrected using the 100-ms prestimulus recording interval and visually inspected for artifacts. Because specific experimental predictions rested on

comparisons between stimulus types and visual inspection for artifacts took place before segment averages were computed for each stimulus type, the artifact rejection procedure could not have biased the outcomes in a particular direction. Individual channels were marked bad if signal amplitudes exceeded 150 μV or if contaminated by eye movements, blinks, or high-frequency noise. An entire trial was excluded from further processing if there were more than nine bad channels. For trials not excluded, bad channel data were replaced by data interpolated from the remaining channels using a spherical spline algorithm. Once all artifacts had been removed and/or corrected, individual subject EEG segment averages were computed for each stimulus type (i.e. Saint Bernards 1–18, Saint Bernards 19–36, novel Saint Bernards, and novel Beagles). Each infant contributed at least 10 artifact-free trials to the individual average for each stimulus type, and all infants who provided at least 10 trials for each of the stimulus types were included in the analyses.

Behavioral testing

At the conclusion of ERP testing, with the net removed, paired-preference trials were administered to provide behavioral evidence that category learning had occurred. There were two 5-s trials during which a novel Saint Bernard was paired with a novel Beagle in a left–right arrangement. The two stimuli were randomly chosen for each infant and different from the Saint Bernards and Beagles presented during ERP testing. Left–right positioning of the stimuli was counterbalanced across infants on the first trial and reversed on the second trial. Two independent observers, both blind to the lateral position of the stimuli, recorded infant looking times from videotape records. Average level of agreement was 97.40% ($SD = 5.19$).

Results

Analyses were based on visual inspection of the waveforms and directed by the few papers in the developmental cognitive neuroscience literature that have identified ERP components associated with recognition memory and categorization in infants (e.g. de Haan, Pascalis & Johnson, 2002; Grossmann *et al.*, in press; Quinn *et al.*, 2006; Reynolds & Richards, 2005; Scott, Monesson & Buchinski, 2008). Following Quinn *et al.* (2006), the choice of electrode groupings was guided by an effort to link specific infant ERP components (e.g. slow wave, Nc, P400) with particular elements of the categorization process (i.e. learning a familiarized category, preferring a novel contrast category). This analysis revealed three time windows and three scalp regions of interest. In addition, after Quinn *et al.* (2006), a priori planned comparisons were used in lieu of more general ANOVAs because the

relevant comparisons are dictated by the specific logic of the categorization procedure. Statistical tests were based on component amplitudes averaged over time and electrode groups.

Category learning at the subordinate level

Amplitude of the Positive Slow Wave (PSW) displayed the pattern of outcomes associated with learning a subordinate-level category of Saint Bernards that would include novel Saint Bernards, but exclude Beagles. As illustrated by the waveform plots in Panel A of Figure 1, greater positive amplitude was recorded over occipital scalp in response to Saint Bernards 1–18 and novel Beagles (reflecting initial experience with category

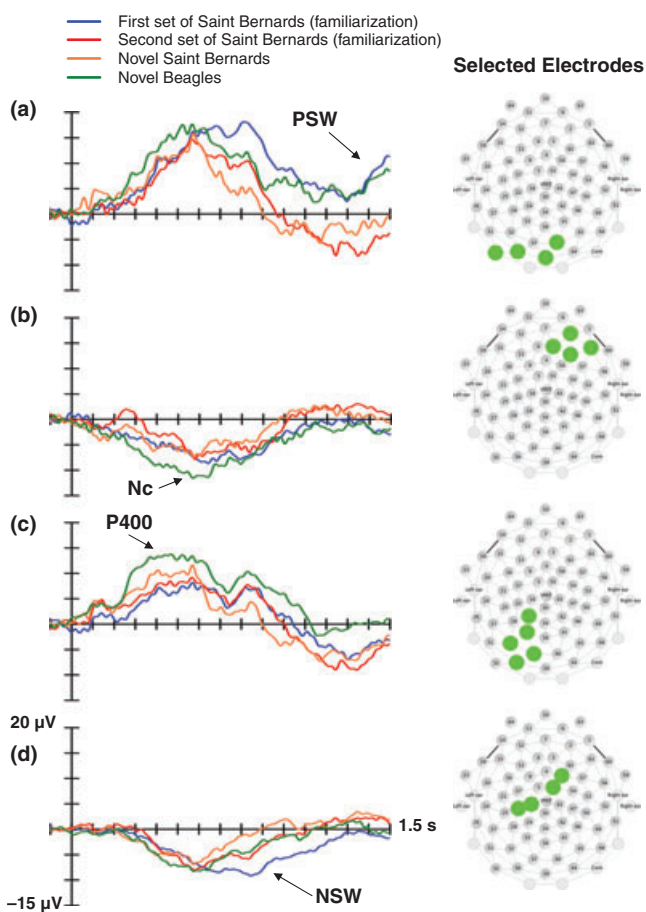


Figure 1 Waveform plots depicting grand average infant ERPs in response to the first set of Saint Bernards (blue), second set of Saint Bernards (red), novel Saint Bernards (orange), and novel Beagles (green). Panel a reflects the Positive Slow Wave (PSW) for a group (average) of occipital electrodes. Panel b depicts the Negative central (Nc) for a group (average) of fronto-central electrodes. Panel c shows the P400 component for a group (average) of occipital-parietal electrodes. Panel d shows the Negative Slow Wave (NSW) for a group (average) of central electrodes. To the right of each plot is a two-dimensional electrode layout of the Geodesic Sensor Net with the selected electrodes corresponding to each ERP component shaded in green.

exemplars) relative to Saint Bernards 19–36 and novel Saint Bernards (reflecting a learned category). For this scalp region, surface maps in Panel A of Figure 2 appear red (more positive voltage) for Saint Bernards 1–18 and novel Beagles, and green and blue (less positive voltage) for Saint Bernards 19–36 and novel Saint Bernards. Planned comparisons showed that average amplitude of the ERP signal in the time window between 900 and 1500 ms after stimulus onset was not significantly different for Saint Bernards 1–18 ($M = 6.96 \mu\text{V}$, $SD = 10.80$) versus novel Beagles ($M = 5.28 \mu\text{V}$, $SD = 10.46$), or Saint Bernards 19–36 ($M = -3.86 \mu\text{V}$, $SD = 15.11$) versus novel Saint Bernards ($M = -2.59 \mu\text{V}$, $SD = 12.44$), $t(9) < 0.38$, $p > .70$, in both cases. However, average amplitude for Saint Bernards 1–18 and novel Beagles combined ($M = 6.12 \mu\text{V}$, $SD = 8.00$) was significantly greater than that for Saint Bernards 19–36 and novel Saint Bernards combined ($M = -3.22 \mu\text{V}$, $SD = 12.19$), $t(9) = 2.35$, $p < .05$.

Novel category preference

Amplitude of the Negative central (Nc) component displayed the expected pattern of outcomes for greater

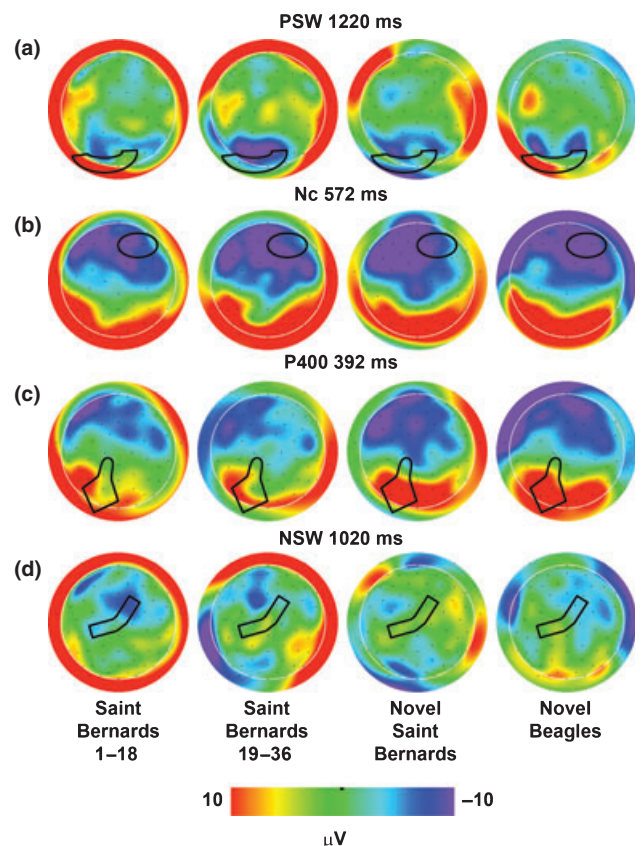


Figure 2 Surface distribution of the average amplitude for the four conditions at 1220 ms (PSW, Panel a), 572 ms (Nc, Panel b), 392 ms (P400, Panel c), and 1020 ms (NSW, Panel d). Scale is from $-10 \mu\text{V}$ (violet) to $+10 \mu\text{V}$ (red). Selected channels used for calculating the ERPs were within the region marked on the scalp topography map by the black frame.

responsiveness to a novel contrast category at the subordinate level. In Panel B of Figure 1, novel Beagles elicited more negative amplitude over fronto-central scalp relative to Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards. For this scalp region, surface maps in Panel B of Figure 2 depict a more expansive band of violet (more negative voltage) for novel Beagles, relative to the dark and light blues (less negative voltage) observed for Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards. Planned comparisons of average amplitude in the time window between 300 and 752 ms after stimulus onset revealed no significant differences between Saint Bernards 1–18 ($M = -6.09 \mu\text{V}$, $SD = 9.03$), Saint Bernards 19–36 ($M = -4.39 \mu\text{V}$, $SD = 4.79$), and novel Saint Bernards ($M = -5.15 \mu\text{V}$, $SD = 6.68$), $t(9) < 0.90$, $p > .39$, in each case. However, average amplitude for novel Beagles ($M = -9.29 \mu\text{V}$, $SD = 5.07$) was reliably different from that for Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards combined ($M = -5.21 \mu\text{V}$, $SD = 6.23$), $t(9) = -2.80$, $p < .05$.

Preferential responding to a novel contrast category at the subordinate level was also evident in the P400 component, a possible marker for face and subordinate-level processing in infants (de Haan *et al.*, 2002; Scott *et al.*, 2008). In Panel C of Figure 1, novel Beagles elicited more positive amplitude over occipital-parietal scalp relative to Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards. For this scalp region, surface maps in Panel C of Figure 2 depict a larger area of red (more positive voltage) for novel Beagles, relative to the greens and yellows (less positive voltage) observed for Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards. Planned comparisons indicated that average amplitude in the time window between 252 and 652 ms after stimulus onset was not significantly different for Saint Bernards 1–18 ($M = 5.71 \mu\text{V}$, $SD = 7.12$), Saint Bernards 19–36 ($M = 6.94 \mu\text{V}$, $SD = 10.27$), and novel Saint Bernards ($M = 8.59 \mu\text{V}$, $SD = 9.73$), $t(9) < 1.29$, $p > .23$, in each case. However, average amplitude for novel Beagles ($M = 12.16 \mu\text{V}$, $SD = 10.28$) was reliably different from that for Saint Bernards 1–18, Saint Bernards 19–36, and novel Saint Bernards combined ($M = 7.09 \mu\text{V}$, $SD = 7.47$), $t(9) = 3.84$, $p < .05$.⁴

⁴ It should be noted that preferential responding to a novel contrast category at the basic level was not evident in the P400 over occipital-parietal scalp in Quinn, Westerlund and Nelson (2006). Although the data were not reported in the earlier paper because the results were null, they are reported here. Planned comparisons indicated that average amplitude in the time window between 250 and 650 ms after stimulus onset was not significantly different for cats 1–18 ($M = 16.64 \mu\text{V}$, $SD = 7.59$), cats 19–36 ($M = 14.43 \mu\text{V}$, $SD = 8.11$), and novel cats ($M = 19.10 \mu\text{V}$, $SD = 6.62$), $t(9) < 1.44$, $p > .18$, in each case. More importantly, average amplitude for novel dogs ($M = 16.65 \mu\text{V}$, $SD = 5.96$) was not reliably different from that for cats 1–18, cats 19–36, and novel cats combined ($M = 16.72 \mu\text{V}$, $SD = 5.59$), $t(9) = .04$, $p > .20$.

Behavioral performance

Preferential responding to the novel category was also observed in the looking-time data recorded during the paired-preference test conducted immediately after ERP recording. All 10 infants preferred the novel Beagle over the novel Saint Bernard, and the group of infants showed a mean novel category preference of 64.48%, $SD = 7.07$, which was significantly higher than the chance value of 50%, $t(9) = 6.48$, $p < .001$, and also reliably higher than the spontaneous preference for Beagles when paired with Saint Bernards, $t(32) = 3.46$, $p < .01$. These results confirm that infants in the current procedure had learned a subordinate-level category representation for Saint Bernards that included novel Saint Bernards, but excluded Beagles. The finding replicates previous reports of categorization for this same category contrast in 6- to 7-month-olds using the behavioral familiarization/novelty-preference procedure (Quinn, 2004; Quinn & Tanaka, 2007).

Discussion

The present study investigated category learning at the subordinate level in 6- to 7-month-olds with electrophysiological (ERP) and behavioral (looking-time) measures. For infants familiarized with Saint Bernards and tested with novel Saint Bernards versus Beagles, different ERP components were associated with different components of the categorization process. In particular, slow wave activity was linked with category learning at the subordinate level. Additionally, the Nc and P400 components reflected preferential responding to a novel contrast category at the subordinate level. To our knowledge, this is the first study to identify the neural correlates of categorization at the subordinate level in infants.⁵

The ERP components associated with categorization by infants at the subordinate level in the present study can be compared to the ERP components that were linked with categorization by infants at the basic level in Quinn *et al.* (2006). Specifically, just as category learning at the global and basic levels in the earlier study was manifest in slow wave activity, so was category learning at the subordinate level in the present study. Furthermore, just as preferential responding to a novel contrast category at the basic level in the earlier study was reflected in an enhanced Nc component (see also Grossmann *et al.*, in press), so was preferential

⁵ The infants were presented with a subordinate-level category contrast (Saint Bernard vs. Beagle), and one of the hallmarks of subordinate-level categories is high between-category similarity. One might therefore argue that the current investigation is examining neural markers for highly similar categories, but not subordinate-level categories *per se*. That is, the infants' neural responsiveness in the task may reflect categorization of two classes that are close in a similarity space rather than subordinate-level categorization (cf. Rakison, 2000).

responding to a novel contrast category at the subordinate level in the present study. The correspondence between the two sets of findings suggests that these ERP components are not idiosyncratic responses to particular category contrasts. Rather, slow wave activity appears to be a general marker of category learning at multiple levels of inclusiveness and Nc activity may be a common indicator for preferential responding to a novel contrast category, at least at the basic and subordinate levels.

The P400 results reported here represent an additional, unique marker for preferential responding to a novel contrast category at the subordinate level.⁶ This finding is consistent with adult work showing that category learning at both the basic and subordinate levels share a common ERP component, i.e. an amplified N170, whereas only subordinate-level learning was marked by a unique ERP component, i.e. an enhanced N250 (Scott *et al.*, 2006). Both the infant and adult findings are consistent with models of object recognition that posit different mechanisms for the identification of basic- and subordinate-level categories (Collin & McMullen, 2005; Murphy & Brownell, 1985; Nguyen & Cottrell, 2005; Tversky & Hemenway, 1984). Moreover, the fact that basic- and subordinate-level recognition share a common ERP component in both infants and adults, and that subordinate-level recognition is marked by a distinctive ERP component in both infants and adults, supports developmental models of categorization that posit continuity between the categories of infants and those of adults (Jones & Smith, 1992; Madole & Oakes, 1999; Quinn & Eimas, 1997; Rakison & Poulin-Dubois, 2001).

The fact that the slow wave activity corresponding with category learning at the basic level in Quinn *et al.* (2006) and at the subordinate level in the present study was associated with different directions of deviation away from baseline (i.e. negative in the earlier study, positive in the present study), and observed over different scalp regions (i.e. left occipital-parietal in the earlier study and occipital in the current study), is also consistent with the idea of distinct mechanisms for categorization of basic- and subordinate-level information.⁷ However, the scalp

⁶ Because it was the only component that was unique to the present study and that was not observed in Quinn *et al.* (2006), one could argue that the P400 may reflect an idiosyncratic response to the perceptual differences between these two particular categories, Saint Bernards versus Beagles. This possibility seems unlikely given that P400 effects have also been observed for perceptual differences between non-dog stimuli in visual recognition memory and categorization tasks (e.g. Scott *et al.*, 2008). Nevertheless, we concede that additional category contrasts (e.g. Tabby vs. Siamese, living room chair vs. beach chair) would be needed to determine whether the P400 is diagnostic for subordinate-level category contrasts more generally.

⁷ The precise relation between the morphology of slow wave activity and category learning in infants is further complicated by the finding that in a study of category learning of birds versus fish versus cars, a slow wave deflecting away from baseline in the positive direction was associated with novel instances from a familiarized category, whereas a slow wave returning to baseline was linked with novel category instances (Grossmann *et al.*, in press).

region differences need to be interpreted cautiously, given the difficulties associated with inferring source locale from scalp region.

While the discussion has thus far emphasized learning at the subordinate level, we also observed evidence consistent with the grouping of Saint Bernard and Beagle exemplars into a basic-level representation of dog, as reflected in the amplitude of the Negative Slow Wave (NSW). As shown in Panel D of Figure 1, greater negative amplitude was recorded over central scalp in response to Saint Bernards 1–18 (reflecting initial experience with exemplars of a category) relative to Saint Bernards 19–36, novel Saint Bernards, and novel Beagles (reflecting a learned representation of Saint Bernards + Beagles). For this scalp region, surface maps in Panel D of Figure 2 display a larger area of blue (more negative voltage) for Saint Bernards 1–18, relative to smaller areas of blue, as well as lighter blue and green (less negative voltage) observed for Saint Bernards 19–36, novel Saint Bernards, and novel Beagles. Planned comparisons revealed that average amplitude in the time window between 800 and 1500 ms after stimulus onset was not significantly different for Saint Bernards 19–36 ($M = -0.33 \mu\text{V}$, $SD = 5.46$), novel Saint Bernards ($M = 1.20 \mu\text{V}$, $SD = 7.28$), and novel Beagles ($M = -0.91 \mu\text{V}$, $SD = 3.45$), $t(9) < 1.09$, $p > .30$, in each case. However, average amplitude for Saint Bernards 1–18 ($M = -3.99 \mu\text{V}$, $SD = 4.72$) was reliably more negative than that for Saint Bernards 19–36, novel Saint Bernards, and novel Beagles combined ($M = -0.01 \mu\text{V}$, $SD = 4.72$), $t(9) = -2.92$, $p < .02$.⁸

As noted in the Introduction, behavioral looking-time studies have provided support for a developmental trend from broad to narrow category representations from 2 to 6 months of age. In Quinn *et al.* (2006), the temporal characteristics of the ERP components were consistent with this progressive differentiation of category levels as the slow wave activity corresponding with global-level learning could be observed some 200 ms before the slow wave activity corresponding with basic-level learning. In the present study, inspection of the waveform plots in Figure 1 reveals that basic-level differentiation (separation of Saint Bernards 1–18 from Saint Bernards 19–36, novel Saint Bernards, and novel Beagles) began at approximately 700 ms after stimulus onset (Panel D), whereas subordinate-level partitioning (separation of Saint Bernards 1–18 and novel Beagles from Saint Bernards 19–36 and novel Saint Bernards) did not begin until approximately 900 ms after stimulus onset (Panel A). Thus, there was a sequential emergence of the basic and

⁸ One might claim that the NSW effect reflects a response to an order difference (i.e. stimuli presented earlier vs. later). However, an account based on serial order would have to explain why the NSW changes categorically between stimuli 1–18 (first half of familiarized Saint Bernards) and stimuli 19–36 (last half of familiarized Saint Bernards), and then does not change from stimuli 19–36 all the way through to stimuli 37–76 (novel Saint Bernards and novel Beagles). The basic-level categorization account can explain the observed pattern of NSW responding, whereas the order account has no ready explanation.

subordinate levels in the present study that is consistent with the global-to-basic emergence in Quinn *et al.* (2006). Both sets of results are in accord with the view that category learning in the domain of objects proceeds from broad to narrow. In addition, the fact that broader, more inclusive category representations emerge before narrower, more exclusive category representations both during early development and during the time course of processing suggests a correspondence between what is observed ontogenetically and microgenetically. This correspondence is more generally supportive of an orthogenic approach to understanding categorization (Werner, 1957), one which emphasizes that mechanisms underlying performance become most transparent as they are revealed in the processes of change at different time scales.

Conclusions

The findings from the current study, taken in conjunction with those from Quinn *et al.* (2006), indicate that (1) slow wave and Nc components of infant ERP waveforms are general markers for processes of category learning on the one hand and novel category preference on the other, (2) novel category preferences for a contrast category at the basic and subordinate levels have the Nc component in common, but novel category preference at the subordinate level is accompanied by an additional P400 component, a finding in keeping with the notion that subordinate-level categorization is governed by mechanisms supplementary to those underlying basic-level categorization, and (3) slow wave activity associated with subordinate-level learning followed that associated with basic-level learning by approximately 200 ms, a result in accord with a coarse-to-fine scheme for the emergence of category partitioning. What is especially noteworthy is that there are several different signals corresponding to different aspects of categorization that are replicable across infant studies and that these signals are related in interesting ways to previous behavioral studies of categorization in infants and to prior behavioral and ERP investigations of categorization in adults. The results thus hold promise for a developmental approach to investigating the cognitive neuroscience of category learning.

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