Research Article

Neural Markers of Categorization in 6-Month-Old Infants

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ABSTRACT—*Little is known of the neural processes that underlie concept-formation abilities in human infants. We investigated category-learning processes in infants both by using a common behavioral measure and by recording the brain's electrical activity (event-related potentials, or ERPs). ERPs were recorded while 6-month-olds viewed cat images during training, followed by novel cat images interspersed with novel dog images during test. The data indicate that distinct neural signals correspond with learning of a category presented during familiarization, preferential responding to a novel category, and representation of category exemplars at multiple levels of inclusiveness. The results suggest that fundamental components of the neural architecture supporting object categorization are functional within the first half-year of postnatal life, before infants acquire language and young children engage in formal learning of semantic categories. The findings are discussed in terms of their implications for models of category learning and development.*

Understanding the process by which discriminably different entities are recognized as members of the same category has been a major objective of the cognitive, neural, and developmental sciences (Edelman, 1987; Mandler, 2004; Murphy, 2002). It is clear that categorization must begin at some point during development, so determining when and how category representations are initially formed, refined, related to other knowledge structures (e.g., theories), linked to words, and expressed in the brain is critically important for understanding the developmental course of human cognition (e.g., Hespos & Spelke, 2004). Behavioral work measuring infants' looking time has demonstrated that even quite young infants categorize visual patterns ranging from abstract forms to realistic images (Mareschal & Quinn, 2001). However, only a few studies have considered the neural correlates of categorization in children (Batty & Taylor, 2002; Ellis & Nelson, 1999), and none have examined the neural markers associated with category formation in infants.

Behavioral investigations of categorization in infants have used a procedure that is based on the preference that infants have for novel stimuli (Fantz, 1964). Presentation of numerous exemplars from a common category is followed by presentation of novel exemplars from the familiar category and novel exemplars from a novel category. Generalization of familiarization to novel exemplars from the familiar category and a preference for novel exemplars from the novel category are taken as evidence that the infants have formed a representation of the familiar category and have perceived the exemplars of the novel category to be noninstances of the familiar category. Three- to 9-month-olds who are familiarized with exemplars of cats (photographs or toy models) will generalize looking-time responsiveness to novel cats and display differential responsiveness to novel dogs (Mareschal, Powell, & Volein, 2003; Quinn, Eimas, & Rosenkrantz, 1993), results that have been taken as evidence that the infants can form a category representation for cats that includes novel cats, but excludes dogs. This interpretation is supported by control conditions showing that there is no a priori preference for dogs and that the infants can discriminate among the cats.

To investigate the neural correlates of category formation in infants, we modified the behavioral novelty-preference procedure for use with a Geodesic Sensor Net composed of 63 electrodes (Tucker, 1993). Six-month-olds were presented with 36 visual cat images during training, followed by 20 novel cat images intermixed with 20 novel dog images during test. In addition, infants' looking times were measured during a behavioral paired-preference test (novel cat vs. novel dog) conducted at the conclusion of event-related potential (ERP) recording and with the net removed.

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We reasoned that brain-based evidence for a category representation for cats that included novel cats but excluded dogs could be manifested in two different ways, one corresponding with learning a category presented during familiarization and the other reflecting preferential responding to a novel contrast category during test. The analytical plan involved breaking out the ERP results into four different conditions: first set of cats (Cats 1–18), second set of cats (Cats 19–36), novel cats, and novel dogs. To investigate whether there is an electrophysiological signature associated with learning a category presented during familiarization, we analyzed whether the response to Cats 19 through 36 and novel cats (reflecting a learned category of cats) differed from the response to Cats 1 through 18 and novel dogs (reflecting initial experience with exemplars of a category). To determine whether there is an electrophysiological signature associated with preferential responding to a novel contrast category, we analyzed whether the response to novel dogs differed from the response to all three sets of cats. This latter comparison was based on the assumption that although responses to novel dogs and the first 18 cats would be equivalent in reflecting initial experience with exemplars of a category, novel dogs were unique in being a novel contrast category presented against the backdrop of a just-learned category of cats.

METHOD

Participants

Mean age of the 10 participants was 195.80 days (*SD* = 20.73 days). Seven were female. Twenty-one additional infants were tested, but excluded because of movement artifacts (*n* = 20) or fussiness (*n* = 1).

Stimuli

The stimuli were colored photographs of cats and dogs, from numerous breeds and in different poses, selected from Siegal (1983) and Schuler (1980). Average luminosity, measured for each image in Adobe Photoshop, ranged from 226.05 to 249.57 for cats (*M* = 237.44) and from 225.54 to 248.42 for dogs (*M* = 240.55). The standard deviations of luminosity values within the images ranged from 25.11 to 69.25 for cats (*M* = 49.36) and from 24.78 to 67.13 for dogs (*M* = 45.25). Area and perimeter were measured in centimeters with a LASICO (Los Angeles, CA) 1281 Area/Line Meter and used to derive a shape estimate (perimeter^2/area) for each image (Zusne, 1970). Shape values ranged from 20.03 to 56.88 for cats (*M* = 36.32) and from 24.28 to 61.65 for dogs (*M* = 38.03). None of the mean differences were significant. These measures helped to ensure that the results of the experiment would reflect responding to "catness" versus "dogness," rather than spurious differences between stimulus sets.

Procedure

ERP Testing

Testing took place within an acoustically shielded and dimly lit room. Each infant sat on his or her parent's lap 60 cm away from a computer monitor that was 48 cm wide by 31 cm high. 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 cats presented during familiarization, novel cats, and novel dogs were randomly selected for each infant. Order of presentation of the familiar cats, and the intermingled presentation of novel cats and novel dogs, was also randomly determined for each infant. Each infant was observed during the testing session via video camera, and on-line judgments were employed to (a) present pictures only when the infant was attending to the monitor and (b) subsequently delete trials during which the infant blinked or looked away after stimulus presentation.

ERP Waveform Analysis

ERPs were recorded against a vertex reference, amplified with 0.1- to 100-Hz band-pass filtering, digitized at a 250-Hz sampling rate, and stored on computer disk. Continuous electroencephalographic data were processed off-line using NetStation 4.0.1 (Electrical Geodesics, Inc., Eugene, OR) and segmented into trials consisting of the 100 ms before the stimulus was presented (baseline trials) and the 1,500 ms after the stimulus was presented. Data were digitally filtered with a 30-Hz low-pass elliptical filter and subsequently edited for artifact. Artifacts were identified on individual channels if signal amplitudes exceeded 150 μV or a running average exceeded 75 μV. A trial was excluded if there were more than eight channels exceeding these thresholds. For each infant, an average was computed for each stimulus type (i.e., Cats 1–18, Cats 19–36, novel cats, novel dogs), and data were rereferenced to the average reference. Each of the 10 infants contributed at least 10 artifact-free trials to his or her individual average for each stimulus type. A baseline correction was applied to the 100-ms prestimulus recording interval.

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 test trials during which a novel cat was paired with a novel dog in a left-right arrangement. The two stimuli were randomly chosen for each infant and different from the novel cats and dogs presented during ERP testing. Left-right positioning of the stimuli was counterbalanced across infants on the first test trial and reversed on the second test trial. Two independent observers, both blind to the lateral position of the cat versus the dog, recorded the infants' looking times from videotape records. Average level of agreement was 92.98% ($SD = 6.09$).

RESULTS

Because the infant categorization paradigm has no precedent in the developmental cognitive neuroscience literature, we were unable to offer specific predictions about which components we would observe and what the functional significance of these components might be. Accordingly, our analyses were based on visual inspection of the waveforms, which revealed two time windows and three scalp regions of interest.

Learning a Category During Familiarization

Amplitude of the negative slow wave (NSW), which has been associated with differential responding to familiar and novel stimuli in ERP studies of simple recognition memory for individual exemplars in infants (de Haan & Nelson, 1997), displayed the hypothesized pattern of outcomes associated with learning a category of multiple exemplars. As illustrated by the waveform plots in the top panel of Figure 1, greater negative amplitude was recorded over left occipital-parietal scalp in response to Cats 1 through 18 and novel dogs (reflecting initial experience with category exemplars) than in response to Cats 19 through 36 and novel cats (reflecting a learned category). For this scalp region, the surface maps in the top panel of Figure 2 appear dark blue (more negative voltage) for Cats 1 through 18 and novel dogs, and green and light blue (less negative voltage) for Cats 19 through 36 and novel cats. Planned comparisons showed that average amplitude of the ERP signal in the time window between 1,000 and 1,500 ms after stimulus onset did not differ between Cats 1 through 18 ($M = -5.01$ μV, $SD = 5.15$) and novel dogs ($M = -5.18$ μV, $SD = 6.08$), or between Cats 19 through 36 ($M = -2.41$ μV, $SD = 7.12$) and novel cats ($M = -0.17$ μV, $SD = 8.51$), $t(9) < 0.76$, $p > .20$, in both cases. However, average amplitude was greater for Cats 1 through 18 and novel dogs combined ($M = -5.09$ μV, $SD = 3.16$) than for Cats 19 through 36 and novel cats combined ($M = -1.29$ μV, $SD = 6.25$), $t(9) = -2.35$, $p < .05$, $\eta^2 = .38$. This analysis reveals that the infants' brains responded to novel cats with activity equivalent to that displayed for Cats 19 through 36. More generally, it points to the neural instantiation of a key behavioral indicant of categorization: responding to the novel as if it is familiar.

Preference for a Novel Category

Amplitude of the negative central (Nc) component, which is thought to provide an index of attentional allocation in infants (Nelson, 1994; Richards, 2003), displayed the expected outcome of greater responsiveness to a novel contrast category than to a familiar category. As shown in the middle panel of Figure 1, novel dogs elicited more negative amplitude over left-central scalp than did Cats 1 through 18, Cats 19 through 36, and novel cats. For this scalp region, the surface maps in the middle panel of Figure 2 depict a region of violet (more negative voltage) for novel dogs, in contrast to a region of blue (less negative voltage) for Cats 1 through 18, Cats 19 through 36, and novel cats. Planned comparisons indicated that peak negative amplitude in the time window between 300 and 750 ms after stimulus onset was not different for Cats 1 through 18 ($M = -11.12$ μV, $SD = 5.53$), Cats 19 through 36 ($M = -11.18$ μV, $SD = 7.22$), and novel cats ($M = -13.04$ μV, $SD = 7.40$), $t(9) < 0.62$, $p > .20$, in each case. However, peak negative amplitude was reliably greater for novel dogs ($M = -15.95$ μV, $SD = 5.59$) than for Cats 1 through 18, Cats 19 through 36, and novel cats combined ($M = -11.78$ μV, $SD = 4.09$), $t(9) = -3.43$, $p < .01$, $\eta^2 = .57$. This pattern of results suggests that the Nc component of the ERP waveform may be a neural marker of novel-category preference in infants.[1]

Behavioral Performance

Preferential responding to the novel category was also observed in the looking-time data recorded during the paired-preference test that was conducted immediately after ERP recording. Nine of the 10 infants preferred the novel dog over the novel cat, and the group of infants showed a mean novel-category preference of 62.52%, $SD = 9.77$, a value that was reliably higher than chance (i.e., 50%), $t(9) = 4.05$, $p < .01$, $\eta^2 = .65$. This result confirms that infants in the current procedure had learned a category representation for cats that included novel cats, but excluded dogs.

Global-Level Category Learning

Category representations in adults are believed to be organized hierarchically, with at least three distinct levels: superordinate or global (e.g., mammal or animal), basic (e.g., cat), and subordinate (e.g., Siamese cat; Rosch, Mervis, Gray, Johnson, & Boyes-Braem, 1976). Functional magnetic resonance imaging and ERP investigations conducted with adults suggest that different brain locations may sort objects into different category levels and that early and late components of brain waves may be differentially sensitive to different category levels (Gauthier, Skudlarski, Gore, & Anderson, 2000; Tanaka, Luu, Weisbrod, & Kiefer, 1999). Comparable work with monkeys has not yet been performed, although single-unit electrophysiological studies in awake, behaving monkeys suggest that the lateral prefrontal cortex is involved in processing category-level information

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[1] One could argue that the Nc effect may reflect an idiosyncratic response to the perceptual differences between these two particular categories, cats versus dogs. This possibility seems unlikely given that the Nc effect has also been observed for perceptual differences between individual stimuli not resembling cats and dogs in visual recognition memory tasks (Reynolds & Richards, 2005). Nevertheless, we concede that additional category contrasts (e.g., chairs vs. tables) will need to be tested to determine whether the Nc effect is diagnostic for basic-level category contrasts in general.

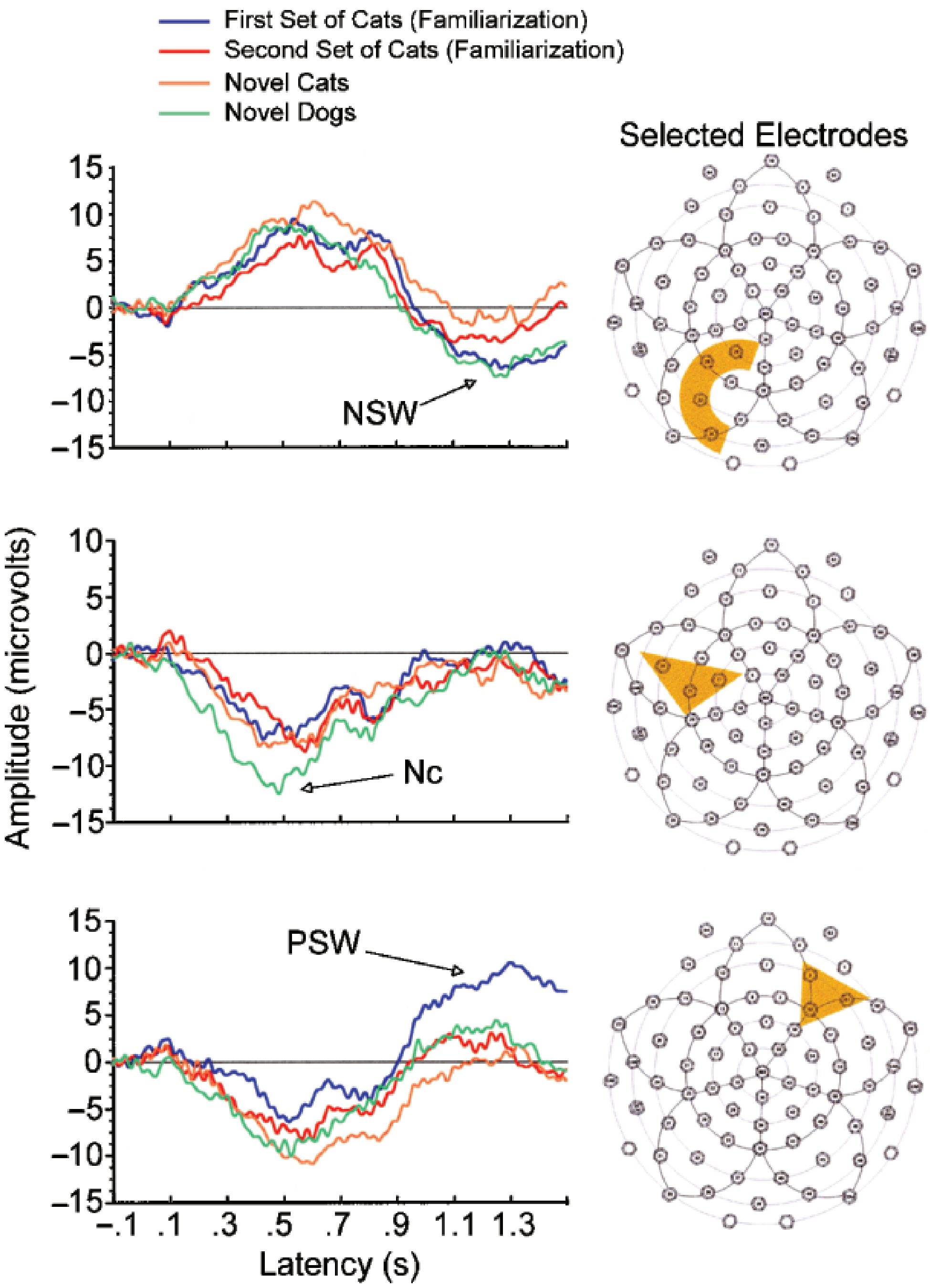

Fig. 1. Waveform plots depicting grand-average event-related potentials (ERPs) in response to the first set of cats presented during familiarization (blue), the second set of cats presented during familiarization (red), novel cats (orange), and novel dogs (green). The top panel reflects the negative slow wave (NSW) for a group (average) of left occipital-parietal electrodes. The middle panel depicts the negative central (Nc) component for a group (average) of left-central electrodes. The bottom panel shows the positive slow wave (PSW) for a group (average) of right frontal electrodes. To the right of each plot is a two-dimensional electrode layout of the Geodesic Sensor Net with the selected electrodes corresponding to the given ERP component shaded.

(Freedman, Riesenhuber, Poggio, & Miller, 2001). Moreover, behavioral studies of categorization in infants have in some instances revealed evidence of representations that are more global or more subordinate than the basic level, but no studies have examined the neural signals associated with these different category levels in infants (Behl-Chadha, 1996; Quinn, 2004).

We uncovered evidence consistent with the grouping of cat and dog exemplars into a global representation of “cat + dog.” In particular, we reasoned that if there is an electrophysiological signature associated with such a representation, then the response to Cats 1 through 18 (reflecting initial experience with exemplars of a category) should differ from the response to Cats

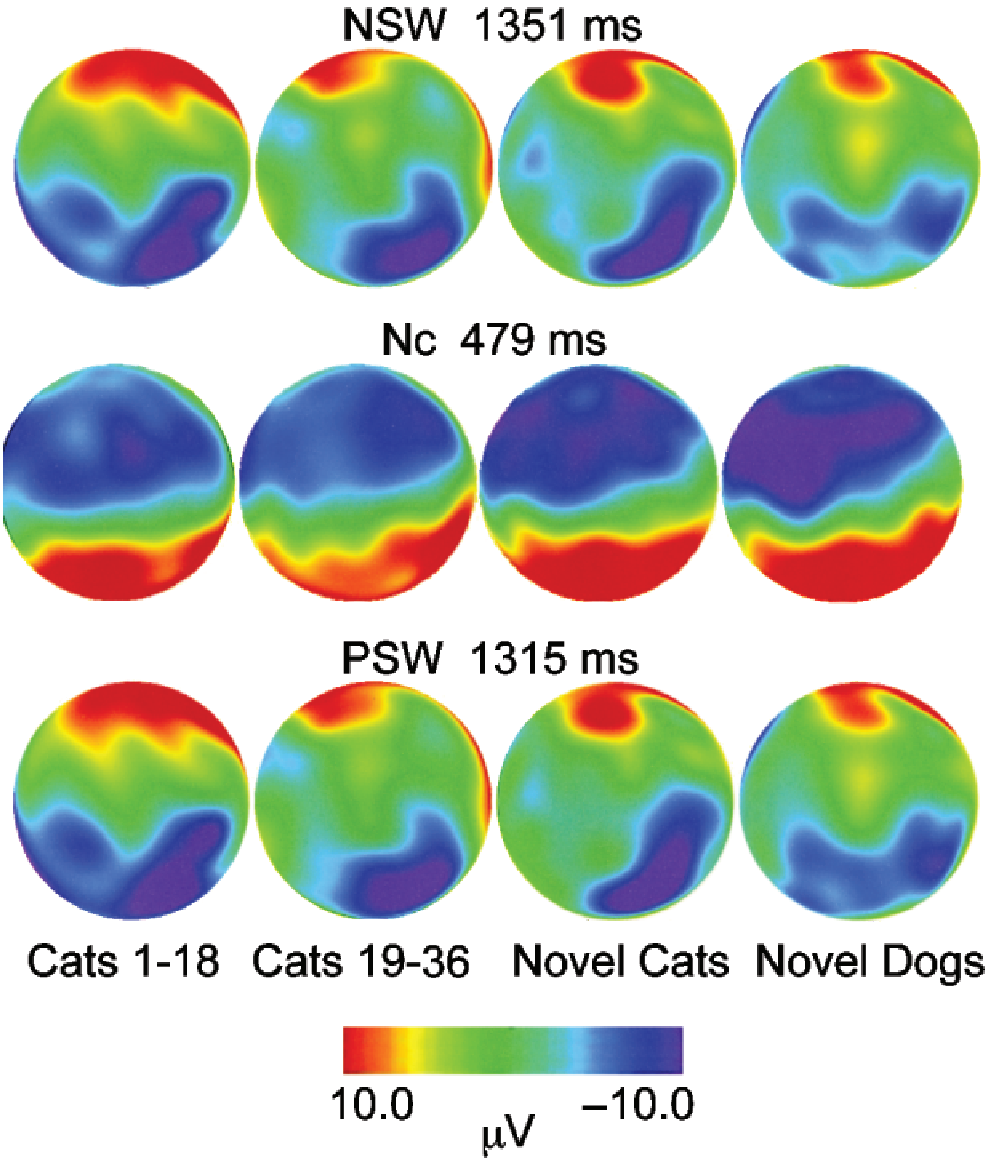

Fig. 2. Surface distribution of the average amplitude for the four conditions. From top to bottom, the maps show the distributions for the negative slow wave (NSW) at 1,351 ms, the negative central (Nc) component at 479 ms, and the positive slow wave (PSW) at 1,315 ms.

19 through 36, novel cats, and novel dogs (reflecting a learned representation of cat + dog). The amplitude of the positive slow wave (PSW) displayed the predicted pattern. As shown in the bottom panel of Figure 1, greater positive amplitude was recorded over right frontal scalp in response to Cats 1 through 18 than in response to Cats 19 through 36, novel cats, and novel dogs. For this scalp region, the surface maps in the bottom panel of Figure 2 reveal red (more positive voltage) for Cats 1 through 18 and yellow-green (less positive voltage) for Cats 19 through 36, novel cats, and novel dogs. Planned comparisons revealed that average amplitude in the time window between 900 and 1,500 ms after stimulus onset did not differ among Cats 19 through 36 ($M = 0.89$ μV, $SD = 7.00$), novel cats ($M = -0.68$ μV, $SD = 13.85$), and novel dogs ($M = 1.99$ μV, $SD = 8.64$), $t(9) < 0.71$, $p > .20$, in each case. However, average amplitude was reliably greater for Cats 1 through 18 ($M = 7.89$ μV, $SD = 6.78$) than for Cats 19 through 36, novel cats, and novel dogs combined ($M = 0.73$ μV, $SD = 7.64$), $t(9) = 2.66$, $p < .03$, $\eta^2 = .44$. These outcomes are consistent with the idea that the PSW component of the ERP waveform represents a neural correlate of global-level category formation in infants.[2]

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[2] One might claim that the PSW 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 PSW changed categorically between Stimuli 1 through 18 (first half of familiar cats) and Stimuli 19 through 36 (last half of familiar cats), and then did not change from Stimuli 19 through 36 all the way through to Stimuli 37 through 76 (novel cats and novel dogs). Global-level categorization can explain the observed pattern of PSW responding, whereas order cannot readily explain it.

DISCUSSION

Category-learning processes in 6-month-olds were measured with both electrophysiological (ERP) and behavioral (looking-time) measures. Distinct components of the ERP signal recorded from different scalp locations were found to reflect particular components of category formation. It is perhaps not surprising to find neural correlates of categorization in infants, because one would expect to find a recordable neural expression for behaviors that have been documented. However, it is significant that there are several different signals corresponding to different aspects of categorization and that these signals are related in interesting ways to previous ERP components associated with attention and memory. That such processes are in place by the age of 6 months indicates a neural preparedness to represent category information on the basis of perceptual experience, before infants acquire language and young children engage in formal learning of semantic categories.

Learning of a Category During Familiarization Versus Preference for a Novel Category During Test

The ERP results suggest that at the basic level of classification, distinct brain activity corresponds to the formation of a category representation for the exemplars presented during familiarization (e.g., cats), on the one hand, and to responding preferentially to a novel category (e.g., dogs), on the other. It is of interest that the NSW response reflecting grouping together the cat exemplars presented during familiarization and test occurred later than the Nc response reflecting differentiation of the dogs. This result is consistent with the idea that grouping multiple exemplars into a common representation during familiarization is a more complex mental operation than discriminating exemplars from novel categories during test (Quinn & Eimas, 1998), and suggests, moreover, that different mechanisms underlie the computation of within-category similarity, on the one hand, and between-category dissimilarity, on the other. This possibility has been raised previously on the basis of data obtained in behavioral studies conducted with adults (Gati & Tversky, 1984; Homa & Chambliss, 1975) and infants (Quinn, 1987), but has not to our knowledge received support from neuroimaging measures in adults or infants.

Implications for Accounts of Infant Categorization

The findings that basic- and global-level category learning are observed over left occipital-parietal and right frontal scalp recording locations in negative and positive slow-wave activity are relevant to competing processing accounts of the representation of category-level information by infants. According to one account, perceptual learning produces progressive differentiation from global to basic levels (Quinn & Eimas, 2000); according to the other, processing of global and basic levels occurs in parallel, and each form of processing is based on the nature of the information represented at that level (i.e., conceptual vs. perceptual; Mandler, 2000).

At a coarse spatiotemporal level of analysis, the fact that the global- and basic-level category signals were articulated in different forms of slow-wave activity recorded from different scalp locations is consistent with a parallel-processing model. However, the two category levels, basic and global, were both formed from perceptual experience (i.e., the presentation of visual images during the experimental task), not from separate sources of information. The fine-grained temporal characteristics of the findings are consistent with the progressive-differentiation model. Inspection of the waveform plots in Figure 1 shows that the global-level differentiation (separation of Cats 1–18 from Cats 19–36, novel cats, and novel dogs) began at approximately 900 ms after stimulus onset (bottom panel), whereas the basic-level contrast (separation of Cats 19–36 and novel cats from Cats 1–18 and novel dogs) did not begin to emerge until approximately 1,100 ms after stimulus onset (top panel). This sequential emergence of the global and basic levels is consistent with the view that category learning in the domain of objects may proceed from broad to narrow as surface-feature differences between categories are progressively extracted from visual input during the course of early experience.

Scalp Topography and Wave Morphology

With regard to scalp topography, as has been reported for adults (Tanaka et al., 1999; see also Schlaghecken, 1998), a changeover from narrow to broader levels of category representation was associated with a shift in activity from more posterior to more frontal sites. This pattern suggests at least a general similarity between the infant and adult brain in the differential engagement of brain regions underlying the processing of different category levels.

At the level of wave morphology, it is informative to compare ERPs in tasks measuring categorization of multiple stimuli from a common class versus tasks involving recognition memory for individual stimuli. In both cases, an enhanced Nc component is associated with novelty detection (compare the Nc reported in the present study with that reported for the familiarization group in Fig. 5 of Reynolds & Richards, 2005). Also in both cases, slow-wave activity shows a return to baseline with recognition of stimuli as familiar, but a deflection away from baseline (in either the negative or the positive direction) with recognition of stimuli as novel (compare the NSW and PSW observed in the current study with those displayed in Fig. 1 of de Haan & Nelson, 1997). The similarity in wave morphology associated with classification of numerous exemplars from a category of stimuli as familiar or novel, on the one hand, and recognition of individual stimuli as familiar or novel, on the other hand, is consistent with single-mechanism models that have been proposed to account for perceptual classification and recognition memory in adults (e.g., Nosofsky, 1991; Nosofsky & Zaki, 1998; see also Curran, Tanaka, & Weiskopf, 2002).

Issues Raised by the Data

The brain wave data obtained in this study with infants raise two related questions. First, given that basic- and global-level categories were formed for the stimuli presented during familiarization, how is it that on the behavioral test of novelty, the two stimuli presented (novel cat and novel dog) were compared with only the familiar basic-level category, resulting in a novelty effect? If the two stimuli were compared with the global-level category (cat + dog), then no novelty effect should have been present. One answer to this question is suggested by the performance of computational models that were constructed to simulate the global-to-basic order of emergence of category representations in young infants participating in behavioral looking-time tasks (Quinn & Johnson, 2000). During initial learning, a majority of representational resources (i.e., hidden nodes) came to encode the global level, with the remaining resources not yet committed. The early global-coding nodes quickly learned to represent large differences in a small number of attributes that distinguished the global level. However, as learning proceeded, more of the network's resources became committed to encoding basic-level distinctions that were characterized quantitatively by smaller value differences along a variety of attributes. Thus, during the course of category learning, there is a decrease in the percentage of representational resources encoding the global level (although this level never drops out of the overall representational scheme) and an increase in the percentage of representational resources encoding the basic level. Greater allocation of representational resources to the basic level could be one reason why this level determines infants' looking preferences when both basic and global levels are represented.

A second question arises from the observation that the global level was formed on the basis of experience with Cats 1 through 18 only, and that Cats 19 through 36, novel cats, and novel dogs all resulted in slow-wave activity characterized by a return to baseline. How did the infants' mind-brain system come to create a level of representation more inclusive (i.e., cat + dog) than what it was experiencing (i.e., cat)? One speculation is that after infants saw the first few cats, their representation came to approximate "four-legged prototypical mammal" or "animal," and that only with the presentation of additional cats did the global representation become refined to produce the basic level. Preference tests with exemplars from nonmammal and nonanimal categories would be needed to investigate this possibility.

Conclusion

However the questions raised by the data are resolved, the evidence suggests a neurophysiological basis in human infants for learning a category during familiarization, preferring a novel category, and responding to category exemplars at multiple levels of inclusiveness. The results indicate that fundamental components of the neural architecture needed to support object categorization processes are functional within the first half-year of postnatal life. Moreover, the findings provide constraints for theoretical accounts of category learning and development that have heretofore not been observed in either behavioral performance or computational simulation.

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