Evidence of Rapid Correlation-based Perceptual Category Learning by 4-month-olds

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Young infants are very sensitive to feature distribution information in the environment. However, existing work suggests that they do not make use of correlation information to form certain perceptual categories until at least 7 months of age. We suggest that the failure to use correlation information is a by-product of familiarization procedures that encourage infants to over encode individual exemplars rather than relations across exemplars. By changing the exemplar presentation regime to one in which exemplars are rapidly (2 s durations) and repeatedly presented we find that 4-month-olds can form perceptual categories on the basis of feature correlation information. In addition, this ability emerges rapidly between 114 and 134 days. We argue that the ability to process correlation information is present very early on but that the demonstration of that ability in categorization tasks is mediated by the demands of the task the infant is tested with. Copyright © 2005 John Wiley & Sons, Ltd.

Key words: infancy; perceptual categorization; catastrophic interference

Perceptual categorization is fundamental for organizing the visual world. Even very young infants can form perceptual categories on the basis of relatively few visual presentations (e.g. Bomba and Siqueland, 1983; Quinn, 1987; Strauss, 1979; Younger and Gottlieb, 1988; Mareschal and Quinn, 2001). However, it appears that younger infants (less than 5 months) form these categories on the basis of the features in the familiarization stimuli, but not on the relations between those features (Younger, 1990). Indeed, Younger and Cohen (1986) found that 4-month-olds did not appear to be sensitive to the correlations between stimulus features when presented with simple static line drawings of animals. That is, they failed to detect violations in the correlations between key animal features such as leg and neck length.

This is somewhat surprising given that the visual system seems to be a very powerful statistical inference engine tuned to the statistics of the natural environment (Field, 1999a,b). Indeed there is increasing evidence that across a
wide range of ages, infants are highly sensitive to the statistical patterns. Several recent studies of sequence learning for streams of speech sounds (Aslin et al., 1998; Saffran et al., 1996) have demonstrated that 8-month-olds can extract the distributional properties of sequences of syllables. Indeed, much of early word learning seems to derive from the ability to encode co-occurrence statistics (Saffran et al., 1996, 1999). At the younger end of the spectrum, infants as young as 2 months are sensitive to the transition probabilities in dynamic visual sequences (Kirkham et al., 2002). Thus, infants appear sensitive to statistical parameters across a range of tasks, modalities, and ages.

With regards to category learning, 3–4-month-olds have been found to form perceptual categories on the basis of feature distribution information (Mareschal et al., 2000, 2002; French et al., 2004). As 4-month-olds are clearly able to form perceptual categories from a relatively small number of examples and are sensitive to statistical information in the environment, this begs the question of why there is no clear evidence of their use of correlational information to form perceptual categories.

One way to resolve this paradox is to shift the research questions away from asking ‘what statistical information are infants sensitive to?’, to asking how the statistical information present in the environment is represented internally. To address this question, Mareschal and French (2000) developed a simple connectionist autoencoder model of infant perceptual category learning in the context of correlated category learning tasks originally developed by Younger and colleagues (Younger, 1985; Younger and Cohen, 1986). In this model, statistical information is gradually encoded in the associative connection weights between the network nodes. However, like most associative networks that continuously update their weights, this model suffers from catastrophic interference (French, 2001). That is, the learning of current material can interfere with, and even overwrite, previously acquired material. This can be a real problem for category learning as categorization requires generalization over a number of different exemplars.

It turns out that the familiarization regime typically used with infants in visual preference and habituation studies can be conducive to catastrophic interference (Mareschal et al., 2002). Infants are typically presented with, and allowed to continuously encode a single exemplar for an extended period of time, (typically 15–30 s in fixed block procedures, but this may vary in infant-controlled procedures) before being presented with the next exemplar. This continues until all exemplars have been presented sequentially and encoded one at a time. The problem with this procedure is that if, during looking, the infants are loading these exemplars into a short-term associative memory system as suggested by the autoencoder model of habituation (Mareschal and French, 2000; Mareschal et al., 2000, 2002), each successive exemplar that the infant encodes will interfere with the representation of the previously stored exemplars. That is, the infant over encodes each individual exemplar encountered during familiarization, and this at the expense of the previously encountered exemplars.

In the networks, one solution to this problem is to give many brief interleaved exposures of the training exemplars rather than a sequence of relatively long exposures to individual training exemplars. This leads to the counterintuitive prediction that increasing the rate of presentation of exemplars (and conversely decreasing the time available for inspection) will improve later performance on categorization tests by young infants. In this manuscript, we explore whether such a procedure will help young infants form perceptual categories on the basis
of feature correlation information. The use of correlation information requires that the infant abstract across several different exemplars. One reason why there has been no published evidence of their ability to use correlation information to form perceptual categories, may be that the sequential presentation procedure typically used encourages them to focus on the last exemplar encountered rather than the set of all exemplars. Thus, in this study, we tested infants with a perceptual categorization task almost identical to that described in Younger (1985) except that infants were familiarized with many brief exposures to the familiarization set rather than a series of single relatively protracted familiarization trials.

METHOD

Participants

Thirty-seven infants took part in the experimental condition (20 girls and 17 boys) with a median age of 128 days (range 114–144). Twenty infants took part in a prior preference control conditions (10 girls and 10 boys) with a median age of 128 days (range 115–142). A further 15 participants were tested but were not included in the analyses either because they failed to look at least 250 ms at both the test items during each of the two test trials (n = 13) or because of parental interference (n = 2). Infants who do not look sufficiently long at both test items within a trial are excluded because it is inappropriate to infer a preference for one stimulus over the other if they have not examined both stimuli.

Stimuli

The stimuli used in the current study were the same as those used by Younger (1985, Experiment 2). Ten schematic animals were constructed for use as familiarization items (see Figure 1(a) for the three examples). The animals differed on four dimensions: leg length, neck length, tail width and ear separation. There were five values on each dimension. Leg length varied from 2 to 7.5 cm, in increments of 1.375; neck length varied from 7 to 1.5 cm, in increments of 1.375; tail width varied from 3.5 to 0.5 cm in increments of 0.75 cm; ear separation varied from 2 to 4.5 cm in increments of 0.625 cm. The stimuli were constructed such that the smallest and largest value (values 1 and 5) on each dimension occurred three times across the set of 10 animals. Value 3 occurred four times on each dimension, with the result that it was both the most frequently occurring value, and also the average, or prototype, of all the experienced values. A further property of the stimulus set was that restricted ranges of values were correlated across the dimensions, with the results that values of 1 occurred with other 1’s and with 3’s, whereas values of 5 occurred with other 5’s and 3’s. Table 1 shows the values that comprised each of the familiarization stimuli.

Three further stimuli were created for use as test items. A stimulus with the value 3 on each dimension (stimulus 3333) was paired with a stimulus with either the value 2 (stimulus 2222) or the value 4 (stimulus 4444) on each dimension. The values comprising stimulus 3333 were both the most frequently occurring values, and also the average, or prototype, of all the experienced values. Stimulus 2222 and stimulus 4444, on the other hand, contained values that had not been
Figure 1. (a) Four of the 10 familiarization stimuli and (b) the three test stimuli. Test stimuli 2222 and 4444 are comprised completely of novel feature values whereas stimulus 3333 is comprised of the most frequent feature values.

Table 1. Composition of familiarization stimuli: values on each of the four dimensions of leg length, neck length, tail width and ear separation

<table>
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<tr>
<th>Fam. Stim.</th>
<th>Leg length (1 = short, 5 = long)</th>
<th>Neck length (1 = long, 5 = short)</th>
<th>Tail width (1 = thick, 5 = thin)</th>
<th>Ear separation (1 = narrow, 2 = wide)</th>
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experienced during familiarization, but which fell within the ranges of correlated values. Thus if the infants formed one category including all the familiarization stimuli, then stimulus 3333 would be more familiar to them than stimulus 2222 or 4444. If, however, the infants were sensitive to the two ranges of correlated values comprising the familiarization stimuli and as a result formed two categories, then stimulus 3333 would be treated as less familiar as it fell at the boundary between the two categories.

**Procedure**

Testing took place in a special-purpose testing cubicle painted grey, and illuminated from above. The stimuli were presented to the infants on a plasma screen measuring $92 \times 52$ cm, connected to a G4 Macintosh computer, using the Habit 2000 infant presentation software (Cohen et al., 2000). Children were seated in a car seat facing the monitor, and at a distance of 80 cm from the screen. Sessions were videotaped to allow later coding of looking time and direction. The monitor was encased in a black curtain. A dull grey partition was positioned to isolate the child from the parent and experimenter, and to hide the experimental control centred from the infant’s view.

Infants in the experimental conditions were presented with a familiarization phase first, followed by a paired preference test phase. Infants in the prior preference control condition were presented only with the paired preference test phase. Thus, differences in the responses of these two groups to the identical test stimuli can be attributed to the effects of the familiarization phase on the experimental group but not the control group.

**Familiarization Phase**

The set of 10 familiarization stimuli was presented four times each, in four blocks of 10 trials. Within each block, the stimuli appeared in quasi-random order, against a light grey background, either on the left or the right side of the screen, with the proviso that an equal number of trials within each block had stimuli appearing at mid-height and 15 cm either to the left or right of the central position. A different fixed random presentation order was generated for each of the four blocks. The order in which the four different fixed randomized blocks of trials were presented to the participants was determined by a repeated $4 \times 4$ Latin Square design.

The familiarization phase started with the presentation of a very attractive central attention-getting stimulus to orient the baby’s attention to the centre of the screen. This stimulus lasted for 6 s and consisted of looming circles accompanied by a varied tone. The four blocks of familiarization stimuli were then presented, with each individual stimulus presentation lasting 2 s. Thus, each block lasted 20 s in total. Each successive familiarization blocks was separated from the previous block by the presentation of the attention-getter for 6 s between each block. At the end of the final familiarization block, the attention-getter was again presented for 10 s. Pilot work suggested that the intervening attention grabbing stimuli were necessary to maintain the infants’ attention towards the monitor throughout the familiarization trials. Because the schematic familiarization stimuli are simple, without the attention-getter, many infants lose interest after only a few exemplars (either becoming fussy or fixating on some other stimulus such as their feet or hands) and fail to form any category representation at all (whether correlation-based or not).
Test Phase

The test phase consisted of the simultaneous presentation of the test pair: stimulus 3333 with either stimulus 2222 or 4444. Each member of the pair appeared in the left and right locations at which stimuli had previously appeared during familiarization. Thus, the paired stimuli were separated by 30 cm stimuli. The test pair was presented for 10 s, followed by the central attention getter for 5 s, and finally the test pair was presented again for a further 10 s, with the left-right positions reversed. The choice of which novel stimulus (2222 or 4444) was used and whether it was initially located on the left or the right was systematically varied across infants.

Scoring

All sessions were videotaped, using a video camera placed above the plasma screen, centred on the infant’s face allowing the experimenter to examine their gaze and to record their behaviour. The amount of time that the infant spent looking at each stimulus was measured by video frames (1 frame = 20 ms). Only those trials in which the infant looked at the stimulus for a minimum of 100 ms was accepted. When the subject blinked and the duration of the blink was longer then 100 ms, we did not include the duration of the blink in the total looking time. Looking times for one-third of the participants were re-scored by an independent observer blind to the experimental hypotheses. The pearson correlations between this observers scores and the original scores ranged from 0.94 to 0.96. The original scores for all subjects were used in the analyses below.

RESULTS

Familiarization Trials

The total looking time (and standard deviations) accumulated in familiarization blocks 1–4, respectively, were: 10.79 s (2.44), 9.07 s (2.60), 8.90 s (3.25), 7.66 s (3.14). The looking times were submitted to an analysis of variance (ANOVA) with block (1,2,3,4) as a within-subject factor, and sex and presentation order as between-subject factors. The ANOVA revealed only a significant effect of block \( F(3, 84) = 16.21, p < 0.005 \). Thus, looking time differed across blocks, but did not differ between sexes or presentation order. Planned contrast also revealed a significant decreasing linear trend \( F(1, 84) = 12.67, p < 0.001 \) but no significant decreasing quadratic trend \( F(1, 84) = 1.28, p > 0.25 \).

Infant looking time decreased with increasing blocks suggesting that the infants were engaged in encoding the stimuli. However, looking times do not appear to level off in later blocks suggesting that infants have not fully habituated. The lack of full habituation suggests that the infant may demonstrate a familiarity preference in testing rather than a novelty preference (Ames and Hunter, 1986; Cohen, 2002; Fiser and Aslin, 2002; Roder et al., 2000; Sirois and Mareschal, 2002). Indeed, whether infants orient more at a familiar or a novel stimulus following familiarization depends on the degree of familiarization, the complexity of the stimulus and the age of the infant. In general, the younger the infant, the more complex the stimuli, and the shorter the familiarization period, the more likely infants will show a familiarity rather than a novelty preference.
Test Trials

For each trial, the difference between the time infants spent looking at the average stimulus (3333) and the time they spent looking at the novel stimulus (2222 or 4444) was computed. A positive values indicates that infants look longer at the average stimulus whereas a negative value indicates that they look longer at the novel stimulus. An initial examination of the difference scores revealed that the variance of the negative scores was much smaller than the variance of the positive score. To homogenize the variances, the differences were transferred using the \( y = \ln(x + 10) \) transformation.

The transformed preference scores for both the infants in the experimental and control conditions were entered into an ANOVA with trial (first, second) as a within-subject factor and condition (experimental, control) as a between-subject factor. Moreover, because the age range in the sample (30 days) represents substantial proportional change in age (24% for the median sample age of 128 days) age was also introduced as a covariate in the form of a condition \( \times \) age interaction. We introduced the age covariate in the form of an interaction because we did not expect any age-related differences in the control condition where the prediction is that of a null effect. The ANOVA revealed a significant condition \( \times \) age interaction \( (F(2, 53) = 4.96, p = 0.01) \) only. In addition, non-parametric analyses (Kendall’s rank correlation coefficient) also revealed a significant associations between the difference in looking time scores and the infants’ age \( (n = 37, z = -1.94, p = 0.05) \) in the experimental condition, but not in the control condition \( (n = 20, z = -0.62, p > 0.52) \).

To examine the condition \( \times \) age interaction further, we carried out separate regression analyses in each of the two experimental conditions. In these analyses, the dependent variable was the difference in looking towards the average stimulus minus the duration of looking towards the novel stimulus averaged across both test trials, and the independent variable was the infants age in days.

In the experimental condition, this analysis revealed a significant linear relationship between the looking time preference and the infants age \( (F(1, 35) = 7.68, p < 0.01) \). Figure 2 shows the regression line as well as the 90% confidence intervals for the true mean value of the looking time difference. The confidence bands marks a region in which there is a probability of \( p = 0.9 \) that the true mean looking time difference will fall for any given age (Kleinbaum et al., 1988). That is, the probability that the mean looking time value falls below the lower bound is \( p < 0.05 \) and the probability that it falls above the upper bound is also \( p < 0.05 \). This figure shows that there is a transition in the infants’ looking behaviour that occurs over the 30 day age range that we tested. Below 124 days of age, the 90% confidence intervals are above and do not include the baseline zero difference point. Thus, infants less than 124 days old show a significant \( (p < 0.05) \) mean preference for the average stimulus. Above 135 of age, the 90% confidence intervals are below and do not include the baseline zero difference point. Thus, infants greater than 135 days old show a significant mean preference for the novel stimulus. In addition, the mean difference score is significantly larger in the younger group than the older group \( (t(17) = 1.89, p < 0.04, \text{one-tailed}) \). These results suggest that there is a shift in the infants’ use of feature correlation information to form feature-based perceptual categories.

This contrasts with the performance of the infants in the control condition. Here, the same analyses revealed no significant linear relation between the infants’ age and looking time duration \( (F(1, 18) = 0.40, p > 0.53) \). In addition, as seen in Figure 3, the mean difference scores never deviate reliable from 0.
These results suggest that there is a change in the way that infants process and use the correlation information in these stimuli from 114 to 145 days. First, at both ends of this spectrum infants formed perceptual categories on the basis of the exemplars that they had encountered during familiarization. This is evinced by a significant preference for looking at one of the test items over the other at both ends of the age range. The younger infants looked longer at the average than the novel stimulus whereas the older infants looked more that the novel than at the average stimulus.

How might this pattern of preferential looking times be interpreted? In Younger’s (1985) original study, infant looking was assumed to reflect a novelty preference. Infants who looked longer at the average stimulus were interpreted as having formed two categories separated by the correlation structure. That is, infants would find this stimulus more novel (even though the stimulus was both the overall average and made up of familiar features) because it lies on the boundary between the two individual categories, and hence is inconsistent with the previously learned category structures. In contrast, infants who looked more at the novel stimuli were interpreted as having formed a single category that did not incorporate the correlation structure between features.

According to this interpretation, the younger infants in our study seem to form two categories that reflect the correlation structure in the familiarization set whereas the older infants seem to form a single category that does not
incorporate feature correlation information. This is a surprising conclusion as it would suggest that infants actually become less sensitive to correlation information over these 30 days.

A key assumption of this interpretation is that infants have habituated to the familiarization set and are showing a novelty preference. However, during the course of habituation, infants initially show a familiarity preference prior to showing a novelty preference (Hunter and Ames, 1988; Cohen and Marks, 2002; Roder et al., 2000; Sirois and Mareschal, 2002). The point in familiarization at which a shift from attending to the familiar to the novel stimulus occurs depends on the infant’s age and the complexity of the stimulus being presented. In particular, younger infants take longer to reach this point than do older infants. Indeed, Younger (1985) was aware of this issue. While infants in her experiment 1 were familiarized using a fixed duration procedure, those in the more rigorously controlled experiment 2 were fully habituated using an infant self-controlled procedure to ensure that they were indeed fully habituated before being tested.

We believe that the infants in the current study are actually showing a familiarity preference rather than a novelty preference. Evidence in support of this can be found in the pattern of looking times during familiarization trials. Here infants showed a significant decreasing linear trend in looking duration with increasing familiarization blocks, but there was no evidence of a quadratic trend. In other words, there is no evidence that the decrease in looking time with increasing block has itself decreased and is asymptoting. This suggests that the infants have not fully habituated to the stimuli. Finally, familiarity effects have

Figure 3. Difference between looking duration to the average minus looking duration to the novel stimulus as a function of age in days in the control condition. Regression line and 95% confidence intervals for the true mean difference, are also shown.
also been found (albeit with older infants) in studies examining infants’ ability to extract feature correlation information from varying sets of stimuli (Fiser and Aslin, 2002).

Working on the assumption that infants are showing a familiarity preference (rather than a novelty preference) we can interpret the looking time pattern in our experimental condition as follows. Infants younger than 124 days prefer to look at the most familiar average stimulus because they have formed a single category that groups the items together on the basis of a feature similarity gradient that does not incorporate feature correlation information. In contrast, infants older than 135 days prefer to look at the novel stimuli. Even though it is made of novel features, it is more familiar that the average stimulus because the average stimulus lies on the boundary between the two categories defined by the correlation structure in the familiarization stimuli. Thus, these older infants have successfully grouped the familiarization exemplars into two perceptual categories on the basis of the correlation structure in the familiarization set.

A stronger test of this hypothesis would be to include a third test trial containing a truly novel stimulus. A preference for looking that the familiar stimulus over this truly novel test stimulus would provide strong evidence of a familiarity preference (Younger and Cohen, 1986). However, care needs to be taken to control for the intrinsic attractiveness of this third stimulus. That is, there should be no prior preference for that stimulus over the other two test stimuli.

In any case, because of the shift in preference that occurs over the age range studied, this data provides evidence that infants in either the older age group or the younger age group have formed a perceptual category on the basis of correlation information in the stimuli. The familiarity preference account we propose above—while somewhat more complex than a straight novelty preference account—provides a more coherent developmental picture.

In addition, these results show that 4-month-old infants can form perceptual categories (either correlation- or feature-based categories) on the basis of rapidly presented stimuli (2 s stimulus durations). We believe that this occurs through a process of implicit internalization of the statistics underlying the distribution of features in the familiarization exemplars (see also Mareschal et al., 2000, 2002). This process is similar to that observed when adult extract prototype and classification information from apparently random checkerboard stimuli that are actually grouped into separate categories (e.g. Posner and Keele, 1970; Fried and Holyoak, 1984).

It is unclear from our results whether the implicit category representation is stored in a short-term memory or visual cache associated with working memory (Ross-Sheehy et al., 2003) and further studies would be needed to tease apart these alternative possibilities. We note, however, that the recent suggestion that the short-term memory capacity of 4-month-olds is limited to 1 item is not inconsistent with our results. We are not in any way suggesting that the infants are remembering each of the different exemplars. In fact, it is precisely because they have limited memory capacity that we believe that the memory system generates summary representations (such as prototypes) which we believe are driving the looking time preferences. Because the infants cannot remember each individual exemplar, the procedure induces the emergence of a summary representation. As further evidence of this we note that 6-month-olds (also reported to have a short-term memory capacity of 1 item) can form perceptual categories of complex images of cats and dogs following the rapid (250 ms) presentation of 18 familiarization exemplars (Quinn et al., in press).
At least on this task, there seems to be a relatively rapid shift in sensitivity to and use of feature correlation information for categorization. Such rapid changes in visual information processing are not unheard of in this age range. For example, a dramatic increase in infants steroacuity occurs between the 15th and 20th week of life (Shimojo et al., 1986). Indeed, one must remember that 30 days represents a substantial proportional change in age at 4 months. However, it is unclear whether the shift we observe reflects a general change in ability or whether it is specific to the task at hand. We believe that the latter option is the most likely. Given the strong evidence of early infant sensitivity to statistical information (e.g., Kirkham et al., 2002; Mareschal et al., 2000; Safran et al., 1996) and the deeply statistical nature of vision, it seems far more likely to us that infants are able to process and utilize correlation information from the earliest age. As this study demonstrates, small changes to the testing procedures can enable infants to demonstrate more fully their abilities. Indeed, Younger (1990) suggest other ways in which task variations may reveal sensitivity to correlation information in categorization tasks.

What causes this change is still an open question. One possibility suggested by Westermann and Mareschal (2004) is that the apparent shift in reliance from similarity- to correlation-based criteria for forming perceptual categories does not reflect a change in the way information is processed, but rather, reflects a shift in infants representational acuity. That is, younger and older infants process visual stimuli in the same way (including processing correlation information), but older infants have more discriminant representational primitives that allow them to demonstrate a sensitivity to correlation information in more perceptually complex stimuli than the younger infant. This hypothesis explains why infants’ age-related sensitivity to correlation information is modulated by the complexity of the stimuli used to test them (Hunter and Ames, 1988).

Some readers may be concerned that the rapid presentation of consecutive stimuli and of an intervening attention holding stimulus during familiarization may lead to the masking of certain category exemplars. However, what little work exists on masking in infants suggests that masking would not occur in our study (Lasky and Spiro, 1983; Catherwood, 1994; Catherwood et al., 1996). These studies have typically used much shorter target stimulus presentations than us (e.g. 100 ms instead of 2 s) and have generally found that for exposure durations of 2 s (as we used) infants fully encode the target stimulus and do not experience masking.

Finally, this work illustrates how models and experimental work can go hand in hand to improve our causal understanding of behaviours. Implemented models provide a tool for investigating information processing mechanisms and allow the investigator to shift his or her emphasis of research from asking ‘what’ infants can do to asking ‘how’ they do what they do.

ACKNOWLEDGEMENTS

This work was supported by Economic and Social Research Council UK grant (R000239112) and by a European Commission RTN grant HPRN-CT-2000-00065. We thank Barbara Younger-Rossman and Les Cohen for helpful comments on an earlier draft of this manuscript. Gert Westermann is now at the Department of Psychology, Oxford Brookes University.

Notes

1. Because of the infants excluded from the analysis, the design of the experimental condition was not completely balanced. Twenty participants were tested with stimulus 4444 and 17 with stimulus 2222. Thirteen initially had the novel stimulus on the left and 24 initially had it on the right. However, an initial ANOVA on the transformed scores with TRIAL (first test trial, second test trial) as a within-subject factor, and sex (boy, girl), novel stimulus identity (2222, 4444), and novel stimulus location (left, right), and condition (experimental, control) as between-subject factors revealed no significant effects or interactions involving sex, novel stimulus identity, or novel stimulus location. Therefore, the data were collapsed across these factors.

2. An alternative possible explanation is that the older infants have actually habituated more deeply than the younger infants and are therefore more inclined to show a novelty preference than a familiarity preference. Indeed, the time it takes to habituate infants to a stimulus decreases with increasing age (albeit no rapid timescales are discussed here). If this were the case, then infants at all ages in the sample would have formed a single category. To test for this possibility, we examined whether preference scores on the test trials were predicted by the amount of habituation computed for each infant as the decrease in looking time between the first and final familiarization block. A simple regression with difference in looking time as the dependent measure and amount of habituation as the independent measure found no evidence of such a relationship (\( F(1, 36) = 0.32, p > 0.57 \)). Thus, looking preferences in test are not differentially determined by the amount of habituation occurring during familiarization. Finally, age did not predict the amount of habituation observed (\( F(1, 35) = 0.03, p > 0.87 \)).

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