Published in final edited form as:

Infancy. 2014 ; 19(3): 262–280. doi:10.1111/infa.12050.

Infant Preference for Natural Texture Statistics is Modulated by Contrast Polarity

Benjamin Balas and

Department of Psychology, North Dakota State University, Center for Visual and Cognitive Neuroscience, North Dakota State University

Rebecca Woods

Center for Visual and Cognitive Neuroscience, North Dakota State University, Department of Human Development and Family Sciences, North Dakota State University

Abstract

Adult observers are sensitive to statistical regularities present in natural images. Developmentally, research has shown that children do not show sensitivity to these natural regularities until approximately 8–10 years of age. This finding is surprising given that even infants gradually encode a range of high-level statistical regularities of their visual environment in the first year of life. We suggest that infants may in fact exhibit sensitivity to natural image statistics under circumstances where images of complex, natural textures, such as a photograph of rocks, are used as experimental stimuli and natural appearance is substantially manipulated. We tested this hypothesis by examining how infants' visual preference for real versus computer-generated synthetic textures was modulated by contrast negation, which produces an image similar to a photographic negative. We observed that older infants' (9-months of age) preferential looking behavior in this task was affected by contrast polarity, suggesting that the infant visual system is sensitive to deviations from natural texture appearance, including (1) discrepancies in appearance that differentiate natural and synthetic textures from one another and (2) the disruption of contrast polarity following negation. We discuss our results in the context of adult texture processing and the "perceptual narrowing" of visual recognition during the first year of life.

INTRODUCTION

In the late 1940s, Hebb (1949) first proposed that repeated experiences influence the organization of neural systems. Since that time, a wealth of research has demonstrated that the statistics of visual experiences have a profound effect on the development of perceptual processes including the detection and recognition of visual stimuli. Indeed, the frequency of complex patterns in the visual environment corresponds to infants' sensitivity to differences between those patterns. A prominent example of how visual experience affects visual recognition can be observed in the development of the other-race effect during the first year of life. The other-race effect is an acquired deficit for discriminating between faces belonging to racial groups with which observers have little experience in the visual

environment. Infants begin showing consistent preferences for own-race faces at approximately 3 months (Kelly et al., 2005), and begin showing robust differences in face discrimination abilities at 9–12 months (Kelly et al., 2007). That is, infants can discriminate other-race faces at 6 months, but lose this ability later in the first year of life. This type of trajectory, in which infants are able to detect or discriminate perceptual stimuli early in infancy, only to lose the ability as they mature, is known as “perceptual narrowing”. Perceptual narrowing occurs in a variety of perceptual domains and has been the focus of a great deal of recent research (Kelly et al., 2007; Lewkowicz & Ghazanfar, 2009; Scott & Monesson, 2010). The time-course of development observed in the other-race effect suggests that a high-level statistical regularity (the predominance of faces belonging to a subset of racial categories) is learned during the first year of life and is malleable for some time beyond that (Bar-Haim, Ziv, Lamy, & Hodes, 2006; de Heering, de Liedekerke, Deboni, & Rossion, 2010). Understanding the phenomenology and the computational principles (Balas, 2012, 2013) that underlie perceptual narrowing in multiple settings is a key step towards determining how recognition processes are shaped by the environment and develop such that observers can quickly and accurately interpret visual input. In the current study, we examine one aspect of this substantive question that has been largely unanswered: How sensitive are infants to the statistical regularities in natural images? Just as infants ultimately accrue experience with some kinds of faces more than others, natural scenes are also a class of images that infants have biased exposure to: Infants predominantly see patterns that respect the statistical properties of the natural visual world. We continue by describing how sensitivity to the statistical regularities of faces develops during infancy as a means of establishing our motivation for investigating how sensitivity to natural texture statistics develops during the first year of life.

Although some face recognition mechanisms appear to require experience, some aspects of face recognition, in particular, more basic visual preferences for faces, appear to be more or less innate. Infants preferentially track face-like patterns minutes after they are born (Goren, Sarty, & Wu, 1975), and this preference is modulated by contrast polarity (Farroni et al., 2005). When contrast polarity is reversed, as it is in a photographic negative, face preferences are disrupted. This suggests that not only is there a bias for face-like patterns that either requires no experience with the visual environment or extremely little experience, but further that this preference is sensitive to the statistical properties that characterize facial appearance (e.g. the contrast relationships resulting from typical illumination (Gilad, Meng, & Sinha, 2009). Overall, investigating the extent to which statistical regularities are learned in infancy contributes to the broad goal of characterizing visual development via explicit computational mechanisms and incorporating visual ecology into theoretical models of development. In particular, a key question in visual development is whether or not perceptual narrowing is a domain-general mechanism that is manifest in multiple contexts (Scott, Pascalis, & Nelson, 2007). Presently, we address this fundamental issue by examining how sensitivity to statistical regularities in natural textures develops during the first year of life. Textures are a particularly convenient means of studying infants’ sensitivity to the regularities in natural images as there are existing methods available to manipulate natural texture appearance so we may compare infant’s visual processing of natural images compared with unnatural ones.

Just as there are statistical regularities that ultimately impact infants' face recognition abilities, natural scenes *in general* have a range of statistical regularities that may similarly shape perception and recognition in early life. Compelling evidence in support of this hypothesis comes from the marked correspondence between the organization of the adult visual system and the statistical regularities evident in natural scenes. Put very broadly, the natural images we encounter are not random; they have consistent structure to which the adult visual system appears to have been tuned. For example, the local luminance (lightness) and local contrast in natural scenes is independent (Frazor & Geisler, 2006)—one cannot reliably predict local luminance from local contrast and *vice versa*. This statistical independence is reflected in the organization of the early visual cortex (Geisler, Albrect, & Crane, 2007). Another example comes from behavioral evidence that reveals a correlation between the adult visual system and the spatial arrangement of luminance values in natural scenes. Natural scenes are highly redundant spatially; it is relatively easy to predict the luminance of a region from the values at nearby regions. Correspondingly, adult observers are quite accurate at predicting the pixel intensity of missing values in digital images of natural scenes (Kersten, 1987). This property of natural images, in concert with computational principles that assume that visual neurons should achieve what is called “sparse-coding” of natural images, offers an account of why V1 receptive fields have the structure that they do (Olshausen & Field, 1996). That is, the receptive fields of cells in the early visual cortex may have been organized in a way to optimally encode the natural scenes an observer will see. In addition to these examples, there are multiple others that demonstrate a close relationship between the statistics of the visual world and the response properties of neurons at different stages of the visual system (see Simoncelli & Olshausen, 2001; Geisler, 2008 for reviews). For our purposes, the important conclusion to be drawn is that the statistics of the visual world do appear to determine visual function.

In addition to the neural evidence that statistical regularities in natural scenes affect visual perception, behavioral evidence demonstrates that adults are particularly sensitive to these properties of natural images. For example, if we consider how much power there is at different spatial frequencies in natural scenes, there is a characteristic function that natural scenes tend to respect. Specifically, natural scenes typically have a $1/f$ power spectrum, which means that across many different natural images, the relationship between low and high spatial frequencies is consistent (Field, 1987; Van der Schaaf & van Hateren, 1996). Psychophysically, adult observers are known to be sensitive to this property. Adult observers who are asked to discriminate between artificial noise patterns that have different values for this slope can typically do so, (Knill, Field, & Kersten, 1990) but they are most sensitive when tested with images that match this property of natural scenes (Tadmor & Tolhurst, 1994; Hansen & Hess, 2006). Pattern discrimination is thus tuned to the statistics of spatial frequencies in the environment.

Just as spatial frequency relationships are “lawful” in natural images, the distribution of orientations, horizontal or diagonal edges for example, also has regularities that adults are sensitive to. The nonuniform distribution of orientations in natural scenes is reflected in adults' sensitivity to gratings at different orientations, such that the visual system appears to be adapted to discount dominant orientations relative to less-frequent ones (Hansen &

Essock, 2004). The adult visual system also appears to be tuned to regularities in natural scenes that are nonuniform, or require observers to encode different statistical regularities in different parts of an image. For example, the distribution of orientations in natural scenes is not spatially uniform: The lower half of natural images tends to have more horizontal edges than the top half. This bias in the environment appears to lead to biases in change detection across the visual field (Alvarez & Oliva, 2009), suggesting that joint encoding of orientation and location is another aspect of how the visual system is adapted to the properties of typical natural scenes. Different categories of natural scenes, such as scenes of cities versus rural environments, have distinct spatial profiles with regard to these nonuniformities (Torralba & Oliva, 2003) and observers can use these category-specific statistical regularities to accomplish scene categorization (Greene & Oliva, 2009). Indeed, aftereffects that bias the perception of specific scene properties can be induced by varying the spatial envelope (Oliva & Torralba, 2001) of an adapting image (Greene & Oliva, 2010). Again, this demonstrates that the adult visual system is sensitive to many aspects of natural image statistics and that the various ways natural structure is represented and encoded leads to measurable advantages (and disadvantages) in perception and recognition.

Broadly speaking, all of these results demonstrate that there are regularities in the visual world, and that these regularities influence visual processing in many ways. Given the preponderance of evidence suggesting that the adult visual system is adapted to natural image statistics, it is logical to ask how that adaptation emerges. Does the visual system require exposure to natural images to become sensitive to the properties of the visual world? If so, does sensitivity to these statistical regularities follow the same developmental trajectory as other aspects of “perceptual narrowing?” Alternatively, is the structure of natural images so constrained by properties of the physical world (e.g. scale invariance—(Ruderman & Bialek, 1994)) that sensitivity to these properties is built in to the visual system? As we have already discussed, the developing visual system is sensitive to the statistics of the visual environment in terms of high-level stimuli like faces. In terms of sensitivity to the statistical properties of natural scenes, there has been relatively little work with children or infants. Children's ability to discriminate between power versus spatial frequency slopes in natural photographs does not appear to reach adulthood until middle childhood (Ellemberg, Hansen, & Johnson, 2012), suggesting that sensitivity to the previously described 1/f spectrum of natural scenes develops over an extended period. Clearly then, the visual system adjusts to the statistics of natural environments at multiple time scales—sensitivity to some statistical regularities are essentially innate, others mature during the first year of life, and still others may be constrained by the extended development of spatial vision (Ellemberg, Lewis, Dirks, & Maurer, 1999) during early to middle childhood.

To our knowledge, there are no previous reports describing infants' ability to distinguish between natural images and images that violate statistical properties of the natural visual world. The lack of such work represents an important gap in our understanding of how visual development proceeds as a function of experience. The structure of the visual world *in general* is likely to be a major factor in shaping infants' recognition abilities at large. Further, we suggest that what data we have (power versus spatial frequency amplitude

discrimination tasks) is likely an inadequate way of examining infants' abilities. Though successfully used with older children (Ellemberg et al., 2012), novel test stimuli that permit deviation from natural image statistics in more sophisticated ways may be required to reveal infants' sensitivity to low-level regularities. Presently, we chose to use a novel technique for manipulating the appearance of experimental stimuli to probe the sensitivity of the infant visual system to low-level natural image statistics.

We investigated infants' sensitivity to natural image statistics using two manipulations of natural texture appearance: Texture synthesis and contrast negation. We chose to use natural textures as a test domain because relatively recent advances in graphics techniques for texture synthesis have made it possible to describe the statistics of natural textures in a manner that relates easily to the human visual system. Moreover, these techniques also make it possible to create images that violate natural appearance systematically. In the current study, we presented infants with paired images of original natural textures and synthetic textures created with a parametric texture synthesis model (Portilla & Simoncelli, 2000). The texture model we used in this study describes texture appearance using several correlations of wavelet coefficients at multiple scales and yields good approximations of texture appearance for a range of different natural stimuli (see Figure 1 for examples of textures made with the model). Adult observers are known to be sensitive to the statistics used to describe appearance in this model (Balas, 2006), and this model has also been successfully applied to more general considerations of how image structure may be encoded by the visual periphery (Balas, Nakano, & Rosenholtz, 2009; Freeman & Simoncelli, 2011; Rosenholtz, Huang, Raj, Balas & Ilie, 2012). We chose to use original and synthetic images in the current study because texture synthesis models make it possible to create a set of stimuli that are well-matched to natural images for appearance but also lack elements of natural structure that are detectable by adult observers (Balas, 2006, 2012). If infants are indeed sensitive to the statistics of natural textures (and by extension, the statistics of natural scenes more generally), the difference between natural and synthetic appearance may lead to a systematic preference for one stimulus pattern over the other.

Besides assessing the basic visual preference for natural versus synthetic texture appearance using a parametric texture synthesis model, we also chose to assess infants' preferential looking using both original and contrast-negated versions of our stimuli. Contrast negation is a powerful means of disrupting natural appearance substantially while preserving many low-level aspects of the original image. Specifically, contrast negation reverses edge polarity across the entire image while preserving the spatial layout of edges and the overall orientation energy of the image (Fleming & Bulthoff, 2005). Contrast negation is known to disrupt face recognition in adult observers (Galper, 1970), and distinguishing natural textures from synthetic textures is more difficult when the stimuli are negated (Balas, 2012), the latter effect suggesting that information that the adult visual system uses for texture discrimination is removed by negation. The perception of shape (Fleming, Torralba & Adelson, 2003) and surface properties (Fleming, Dror, & Adelson, 2003) are disrupted by contrast negation, both of which may contribute substantially to natural texture perception. By negating the stimuli that we present to infant observers in our study, we thus have an additional means of assessing the extent to which the infant visual system is sensitive to the

statistics of natural images. If the infant visual system is tuned to the statistics of natural scenes, we anticipate that contrast-negation should modulate infant preference.

There are several possible outcomes we expected we might observe regarding infant preference for natural versus synthetic textures in our experiment, each of which would suggest different levels of sensitivity to natural image statistics. First, infants might exhibit a systematic preference for natural or synthetic textures regardless of the contrast polarity of the stimuli. This outcome would suggest that infants are sensitive to the violations of natural appearance that are the result of discrepancies between synthetic images and natural images, but insensitive to the disruption of phase statistics that accompany contrast negation. Alternatively, infants may exhibit a preference for natural versus synthetic appearance that is modulated by contrast polarity—exhibiting either a null preference following polarity reversal or a preference that changes direction in response to the disproportionate effects of negation on natural textures relative to synthetic ones (Balas, 2012). Either result would indicate that infants are not only sensitive to the statistical differences between real and synthetic textures, but also that the developing visual system is sensitive to the disruption of natural contrast relationships. Finally, we could also observe (as predicted by previous results) that infants do not have a systematic preference for real or synthetic texture images under either circumstance. This latter result would support the idea that the developing visual system requires either more exposure to natural scenes, ongoing maturation of the visual system, or both, to adequately discriminate between real and artificial patterns.

METHODS

Subjects

Forty-eight healthy full-term infants participated in this study, 18 3.5- ($M = 3$ months, 14 days, range = 3 months, 0 days to 4 months, 1 day), 15 6.5- ($M = 6$ months, 13 days, range = 6 months, 0 days to 6 months, 28 days), and 16 9.5-month-olds ($M = 9$ months, 15 days, range = 9 months, 0 days to 9 months, 29 days). These age groups were selected because they correspond to previously reports of “perceptual narrowing” for face recognition. For example, the visual preference for own-race faces is evident at the age of 3 months (Kelly et al., 2005), and infants exhibit looking behavior consistent with the other-race (Kelly et al., 2007) and other-species effects (Pascalis, de Haan, & Nelson, 2002) at 9 months, but not 6 months. Our choice of age groups is thus motivated by a desire to determine how the development of sensitivity to statistical regularities in natural scene statistics corresponds to the development of sensitivity to statistical regularities in facial appearance during the first year of life.

Fourteen infants were excluded due to distractions during the procedure (e.g., bowel movements) ($N = 4$), completing fewer than 6 trials ($N = 3$), or exhibiting a clear side preference ($N = 7$). Participants were recruited from a mid-sized Midwest town and surrounding areas. Infants were predominantly Caucasian ($N = 45$) and had at least one parent who was a college graduate ($N = 42$). Parents provided demographic information and informed consent prior to the experiment.

Stimuli

Twenty images were printed in 20.5 cm diameter circles. Ten were of photographed objects (e.g., rocks, chains, paper clips) and ten were computer-generated images of the same objects created using the Portilla–Simoncelli algorithm (Portilla & Simoncelli, 2000). Half of these images were photo-negatives created by reversing contrast polarity in the GIMP image-editing application. These stimuli were arranged into 10 pairs; each pair was comprised of a photograph and its computer-generated match. Pairs were mounted 26.5 cm apart and centered top to bottom, on a black matte board measuring 51 cm × 81 cm. Centered between each image was a small viewing hole through which an experimenter could observe the infants' eyes.

The Portilla–Simoncelli algorithm matches synthetic texture appearance to an original texture using texture descriptors that include statistical moments of the image intensity histogram, and multiple correlations between complex wavelet coefficients across position, orientation, and scale. We chose this model because the texture descriptors used to model appearance are biologically plausible, and the model has recently been used to model adult peripheral vision in multiple domains (Balas et al., 2009; Rosenholtz et al., 2012). A detailed description of the model's implementation can be found in the original report by Portilla and Simoncelli (2000) and a summary of the texture descriptors can be found in the Appendix to Balas et al. (2009). We generated synthetic textures using the default parameters of the model and obtained good convergence for all the images used in the study. Additionally, we matched the intensity histograms of each real/synthetic pair presented in the experiment, to further ensure that the mean luminance and contrast of image pairs were matched closely. The Portilla–Simoncelli algorithm does explicitly match moments of the intensity histogram, but we carried out this additional step to match the full histogram of each pair as well. Figure 1 depicts all of the textures we used in the current study, including the original texture, a synthesized texture made from the original, and contrast-negated versions of each of these.

Procedure

A forced-choice preferential looking procedure was used. Infants sat on a parent's lap in front of a black table and across from the experimenter. White curtains concealed the testing room from the infant's view. Once each session began, the experimenter placed the matte board upright on the table at a viewing distance of approximately 80 cm (visual angle of 14.6°). The viewing order of the 10 pairs of stimuli (5 per condition) was randomized. Each board was presented to the infant for up to 5 sec, beginning from the onset of the infant's first look to the stimulus. Though this is a relatively short amount of time compared with some prior studies that have used 30- or 60-sec trials to measure preference, we found in pilot testing that our attrition rate was substantially larger with a longer (20-sec) presentation time. Although 5 sec is relatively short, infants in our task consistently made multiple gaze switches between the left and the right stimulus during each trial. During trials, an experimenter watched the infant's gaze through the viewing hole in the center of the board and made a decision about the direction the infant was looking (to the left or right image). The experimenter's judgment of left versus right preference on each trial was based on their online estimate of the total fixation time allotted to each side of the display during the trial.

Once a decision was made, the experimenter continued to the next board. If the infant did not look at the board, the experimenter tapped the back center of the board to get the infants' attention. If the infant did not look within 5 sec, the trial was coded as an "off" look. A second rater coded direction of infants' looks from video recordings of 44 of the 48 infants using the same criterion as the experimenter who administered the task (infants' eyes were not clearly visible in four recordings). Inter-rater agreement was 86% (agreement for eight or more of the 10 trials).

Each trial could thus be coded as either a look to the left, a look to the right, or as an "off" look which we discarded. We chose not to present discarded trials to infants later in the session, largely because "off" looks could potentially have allowed the infant to see the textures briefly, and infants' behavior during a second presentation of the test stimulus may be affected by their previous exposure to the stimulus. All of the infants in our sample had no more than three discarded trials. Our sample of 3-month-olds contained two infants with a single discarded trial and one infant with three discarded trials. Our sample of 6-month-olds contained two infants with a single discarded trial, three infants with two discarded trials, and two with three discarded trials. Finally, our sample of 9-month-olds contained two infants with a single discarded trial. A one-way ANOVA with age as a between-subjects factor revealed no main effect of age ($F_{(2,45)} = 1.13, p = .33$) on the number of trials completed in the task.

Our design, in which each participant completed a total of 10 trials (five positive and five negative trials), precludes a number of interesting analyses. For example, we cannot meaningfully assess whether or not an *individual* infant exhibits a significant preference for real versus synthetic textures in either condition. Likewise, we also cannot meaningfully discuss the extent to which individual textures elicit a consistent visual preference. However, despite these shortcomings, our design is consistent with a number of recent studies using visual preference for one of two salient images drawn from the same class (e.g. faces—Kelly et al., 2005, 2007; toys—Alexander, Wilcox, & Woods, 2009, Campbell, Shirley, Heywood, & Crook, 2010) to draw conclusions about the developing visual system. In particular, our design is consistent with the techniques used in prior studies of simple artificial textures (Atkinson & Braddick, 1992). Finally, to appropriately address the low signal-to-noise ratio in our data as well as the likelihood that our data will deviate from normality, we analyzed our results using the appropriate nonparametric tests.

RESULTS

To examine the extent to which contrast negation modulated the preference for real/artificial texture appearance, we carried out Related-Samples Wilcoxon Signed Rank Tests within each age group to compare the proportion of trials in which infants preferred to look to the natural texture image in the positive and negative contrast conditions. A preliminary analysis revealed no effect of participant sex, so we report the results collapsed across male and female observers.

We found no difference in the proportion of trials where a preference for natural textures was observed as a function of contrast polarity at 3 months of age ($p = .825$) and 6 months

of age ($p = .75$). However, at 9 months of age, we observed a difference between the positive and negative contrast conditions ($p = .012$) such that infants looked more at the natural texture in the negative polarity trials ($M = 61\%$) than in the positive polarity trials ($M = 40\%$). Although the within-participants comparison between the positive and negative conditions is the most direct test of whether or not contrast polarity affects natural texture preference, we also examined whether or not infants displayed a significant preference for natural textures in each condition separately. We compared the median of each cell in our design (each combination of age and contrast polarity) to a chance value of 50% using One-Sample Wilcoxon Signed Rank Tests. This analysis revealed that only 9-month olds in the negative contrast polarity looked significantly longer at the natural texture ($p = .007$), with no other values significantly deviating from chance. Average proportions for infants in each age group and contrast condition are displayed in Figure 2.

DISCUSSION

Our results demonstrate that infants are sensitive to natural image statistics in the context of naturalistic texture images. The extent to which 9-month-old infants preferred to look at original photographic textures versus synthetic approximations of those same textures was affected by the contrast polarity of the stimuli. Contrast-negation induced a larger preference for the original texture image. Our data thus suggest that in the first year of life, infants have acquired an estimate of natural image statistics that is sensitive to deviations from typical appearance, contra recent results suggesting that sensitivity to natural image statistics does not emerge until middle childhood (Ellemborg et al., 2012). While the current study does not speak directly to the sensitivity of the infant visual system to the specific instance of amplitude fall-off coefficients in natural images, we have shown that infant visual preference to natural images is modulated by natural appearance in a manner consistent with results obtained from adults (Balas, 2012). We thus cannot say that the developing visual system is sensitive to natural image structure to the same degree as the adult visual system, but rather that infants have encoded some implicit knowledge of natural image statistics in the first year of life and that this affects their looking behavior to complex stimuli. Further, it does not seem easy to interpret our data within the framework of perceptual narrowing as we might imagine applying the theory to natural scenes. In particular, the simplest interpretation of how perceptual narrowing might be manifest in this domain would predict that contrast-negated textures should fall outside the “perceptual window” defined by infants’ visual experience and thus be very hard to discriminate between by 9 months of age, which is not what we found. Natural texture appearance thus does appear to matter to the infant visual system, but not necessarily in a manner that clearly reflects “narrowing” of the visual system for natural images that is strictly analogous to the effects observed in the face recognition literature.

Our results do, however, complement previous reports that infants are sensitive to various texture features and can use local statistics to estimate image properties. For example, infants are capable of using texture gradients to estimate depth relationships at approximately 7 months of age (Yonas, Granrud, Arterberry, & Hanson, 1996). Infants can also use differences between texture features to segment images into discrete regions (Arcand et al., 2007; Braddick & Atkinson, 1992; Pei, Pettet, & Norcia, 2007), suggesting

that statistical comparisons between artificial textures (e.g. oriented line segments) are mature relatively early. In both cases, however, we note that the stimuli used to assess infants' texture-processing abilities are sparse, artificial stimuli. While these are useful for controlling low-level stimulus properties, they do not inform us about infants' sensitivity to the properties of real-world textures, and their ability to estimate useful image properties from noisy, cluttered inputs. Moreover, demonstrations that infants can use texture to estimate the number of surfaces, the number of objects, or the depth relationships in a complex image do not allow us to conclude that infants have encoded the statistical regularities that define natural images. Rather, these reports demonstrate that infants have learned a mapping between specific texture relationships and other scene properties. Our results suggest that not only can infants use statistical features to accomplish specific tasks and estimate scene parameters, but that they are sensitive to the broad statistical regularities that characterize natural images. The modulation of infants' preference for real versus synthetic textures by contrast polarity suggests that the developing visual system is sensitive to the violation of natural contrast relationships that accompany negation independent of a particular visual task. To our knowledge, this is the first evidence that infants have encoded some of the statistical regularities of the visual environment and are sensitive to deviations from those regularities.

There are several possible accounts for why younger infants (3- and 6-month olds) demonstrated no sensitivity to the manipulation of contrast polarity and also exhibited no tendency to prefer natural textures to synthetic ones or *vice versa*. The simplest explanation is that perceiving the difference between the natural and synthetic images that we employed here requires greater maturity of visual acuity and/or contrast sensitivity—the critical differences between the two stimuli presented on each trial may have been impossible for younger infants to discern. Both acuity and contrast sensitivity continue to develop over the first year of life (Braddick & Atkinson, 2011), and it is possible that with appropriate scaling of the stimuli or selection of larger-scale textures, younger infants might be capable of distinguishing between the two stimulus types. Besides these basic visual features, more complex image properties might also be less efficiently processed in early infancy, leading to a failure to exhibit a visual preference in our task because of an inability to detect differences between the stimuli presented on each trial. Some of the most conspicuous differences between the synthetic textures we created and the original images result from the model's failure to capture extended contours and global structure. Young infants typically do not perform well at visual tasks requiring similar forms of closure (Baker, Tse, Gerhardstein, & Adler, 2008), raising the possibility that their lack of systematic preferences in this task may also be a function of their inability to integrate information appropriately across larger spatial scales. One way to address this in future studies would be to either “lesion” the Portilla–Simoncelli model used here (Balas, 2006) so that more substantial disruptions of natural appearance are evident in the synthetic images, or to use other texture synthesis models that use only marginal orientation statistics (Heeger & Bergen, 1995). Nonparametric synthesis models that use image quilting to construct a new texture from fixed-size patches of the original could also be a useful means of determining the extent of spatial integration infants are capable of in natural texture images (Efros & Freeman, 2001). Finally, it could also be the case that younger infants can detect the difference between the

two stimulus classes but simply have no consistent preference for one kind of pattern compared to the other. Differentiating between these accounts would either require that we re-configure our stimuli so that we could use visual preference to investigate the detectability of stimulus differences using habituation or visual paired-comparison paradigms (Fantz, 1964) with the same stimuli. Overall, our results demonstrate that older infants are sensitive to violations of natural image structure, but do not rule out the possibility that younger infants could also be sensitive to more conspicuous deviations. As such, we cannot fully address the question of whether or not sensitivity to natural image statistics is innate or learned, but our results do clearly demonstrate that infants exhibit some sensitivity to natural scene structure in the first year of life.

An interesting question raised by our results from 9-month-old infants is what particular aspects of image structure the developing visual system is sensitive to at this stage. The fact that real/synthetic image pairs were closely matched for a range of image statistics suggests that performance in this task was likely not supported by pre-attentive mechanisms, but may instead rely heavily on visual or visuo-cognitive processes that require scrutiny. The Portilla–Simoncelli model is obviously not a complete model of early vision, so we cannot rule out the possibility that some set of image statistics not constrained by the model supports performance in this task. However, previous results from adult observers (Balas, 2006) suggest that the differences between real textures and P–S syntheses are not available pre-attentively, and therefore that higher-order processes may play a critical role in driving infants' preferences in this task. One possible example of such a higher-order feature, given the modulation of visual preference by contrast polarity at this age, is that the perception of material properties like gloss and translucency may be a key factor in the current task. The texture images we selected had multiple specularities, and the negation of these features (and thus the local skewness (Sharan, Li, Motoyoshi, Nishida, & Adelson, 2008) may have been a particularly salient cue to infants that natural image statistics had been violated. Alternatively, contrast negation is also known to substantially disrupt the computation of shape-from-shading (Fleming et al., 2003). The disruption of normal shading cues to depth in our texture images following contrast negation may also be an important determiner of infant preference. This may interact with material properties in interesting ways as well, because specularities provide information about local shape (Fleming, Torralba, & Adelson, 2004) and reversing the polarity of specularities may thus be particularly salient to infant observers in negated images of natural textures. In either case, the current data limit our ability to make strong claims about these hypotheses, but future studies examining a wider range of textures, including matte textures, random textures like sand and dirt, and textures with varying amounts of depth, would make it possible to identify what specific visual properties infants can measure in natural textures.

Finally, besides constraining ourselves solely to relatively uniform textures, using nonstationary image patches taken from cluttered natural scenes would be an additional means of examining the generality of older infants' sensitivity to natural image structure. Recent results from “baby-cam” studies (Aslin, 2010; Yoshida & Smith, 2008) could be particularly useful to guide a broader examination of infants' implicit encoding of image statistics, as their sensitivity to particular statistical properties may be highly constrained by the subset of images they actually see in early life (Smith, Yu, & Pereira, 2010). Overall, our

current results demonstrate that late in the first year of life, infants are sensitive to higher-order differences in appearance between real and synthetic textures. Older infants' visual preference for natural scenes relative to synthetic images is affected by contrast polarity, suggesting that the developing visual system is sensitive to natural contrast relationships in complex textures, possibly because infants are capable of using shading cues and specularities to infer local shape and/or material properties. This result provides an important foundation for continued investigation of how the statistics of visual experience impact perception in developmental time.

REFERENCES

- Alexander GM, Wilcox T, Woods R. Sex differences in infants' visual interest in toys. *Archives of Sexual Behavior*. 2009; 38:427–433. [PubMed: 19016318]
- Alvarez GA, Oliva A. Spatial ensemble statistics are efficient codes that can be represented with reduced attention. *Proceedings of the National Academy of Sciences*. 2009; 106:7345–7350.
- Arcand C, Tremblay E, Vannasing P, Ouimet C, Roy MS, Fallaha N, McKerral M. Development of visual texture segregation during the first year of life: A high-density electrophysiological study. *Experimental Brain Research*. 2007; 180:263–272. [PubMed: 17265040]
- Aslin R. How infants view natural scenes gathered from a head-mounted camera. *Optometry and Vision Science*. 2010; 86:561–565. [PubMed: 19417702]
- Atkinson J, Braddick OJ. Visual segmentation of oriented textures by infants. *Behavioural Brain Research*. 1992; 49:123–131. [PubMed: 1388795]
- Baker TJ, Tse J, Gerhardstein P, Adler SA. Contour integration by 6-month-old infants: Discrimination of distinct contour shapes. *Vision Research*. 2008; 48:136–148. [PubMed: 18093632]
- Balas B. Texture synthesis and perception: Using computational models to study texture representations in the human visual system. *Vision Research*. 2006; 46:299–309. [PubMed: 15964047]
- Balas B. Contrast-negation and texture synthesis differentially disrupt texture discrimination. *Frontiers in Perception Science*. 2012; 3:515.
- Balas B. Developing Race Categories in Infancy via Bayesian Face Recognition. *Visual Cognition*. 2013; 21:1138–1164. [PubMed: 24723788]
- Balas B, Nakano L, Rosenholtz R. A summary-statistic representation in peripheral vision explains visual crowding. *Journal of Vision*. 2009; 9:1–18.
- Bar-Haim Y, Ziv T, Lamy D, Hodes RM. Nature and nurture in own race face processing. *Psychological Science*. 2006; 17:159–163. [PubMed: 16466424]
- Braddick O, Atkinson J. Visual segmentation of oriented textures by infants. *Behavioural Brain Research*. 1992; 49:123–131. [PubMed: 1388795]
- Braddick O, Atkinson J. Development of human visual function. *Vision Research*. 2011; 51:1588–1609. [PubMed: 21356229]
- Campbell A, Shirley L, Heywood C, Crook C. Infants' visual preference for sex-congruent babies, children, toys and activities: A longitudinal study. *British Journal of Developmental Psychology*. 2010; 18:479–498.
- Efros, AA.; Freeman, WT. *Image quilting for texture synthesis and transfer*. SIGGRAPH; Los Angeles, CA: 2001.
- Ellemberg D, Hansen C, Johnson A. The developing visual system is not optimally sensitive to the spatial statistics of natural images. *Vision Research*. 2012; 67:1–7. [PubMed: 22766478]
- Ellemberg D, Lewis T, Dirks M, Maurer D. Development of spatial and temporal vision during childhood. *Vision Research*. 1999; 39:2325–2333. [PubMed: 10367054]
- Fantz RL. Visual experience in infants: Decreased attention to familiar patterns relative to novel ones. *Science*. 1964; 146:668–670. [PubMed: 14191712]

- Farroni T, Johnson MH, Menon E, Zulian L, Faraguna D, Csibra G. Newborns' preference for face-relevant stimuli: Effects of contrast polarity. *Proceedings of the National Academy of Sciences*. 2005; 102:17245–17250.
- Field DJ. Relations between the statistics of natural images and the response properties of cortical cells. *Journal of the Optical Society of America. A*. 1987; 4:2379–2394.
- Fleming R, Bulthoff HH. Low-level image cues in the perception of translucent materials. *ACM Transactions on Applied Perception*. 2005; 2:346–382.
- Fleming RW, Dror RO, Adelson EH. Real-world illumination and the perception of surface reflectance properties. *Journal of Vision*. 2003; 3:347–368. [PubMed: 12875632]
- Fleming RW, Torralba A, Adelson EH. Specular reflections and the perception of shape. *Journal of Vision*. 2003; 4:798–820. [PubMed: 15493971]
- Fleming RW, Torralba A, Adelson EH. Specular reflections and the perception of shape. *Journal of Vision*. 2004; 4:798–820. [PubMed: 15493971]
- Frazor RA, Geisler W. Local luminance and contrast in natural images. *Vision Research*. 2006; 46:1585–1598. [PubMed: 16403546]
- Freeman J, Simoncelli EP. Metamers of the ventral stream. *Nature Neuroscience*. 2011; 14:1195–1201.
- Galper RE. Recognition of faces in photographic negative. *Psychonomic Science*. 1970; 19:207–208.
- Geisler W. Visual perception and the statistical properties of natural scenes. *Annual Review of Psychology*. 2008; 59:167–192.
- Geisler WS, Albrect DG, Crane AM. Responses of neurons in primary visual cortex to transient changes in local contrast and luminance. *Journal of Neuroscience*. 2007; 27:5063–5067. [PubMed: 17494692]
- Gilad S, Meng M, Sinha P. Role of ordinal contrast relationships in face encoding. *Proceedings of the National Academy of Sciences*. 2009; 106:5353–5358.
- Goren CC, Sarty M, Wu PY. Visual following and pattern discrimination of face-like stimuli by newborn infants. *Pediatrics*. 1975; 56:544–549. [PubMed: 1165958]
- Greene MR, Oliva A. Recognition of natural scenes from global properties: Seeing the forest without representing the trees. *Cognitive Psychology*. 2009; 58:137–176. [PubMed: 18762289]
- Greene MR, Oliva A. Adapting to scene space: High-level aftereffects to global scene properties. *Journal of Experimental Psychology: Human Perception and Performance*. 2010; 36:1430–1432. [PubMed: 20731502]
- Hansen BC, Essock EA. A horizontal bias in human visual processing of orientation and its correspondence to the structural components of natural scenes. *Journal of Vision*. 2004; 4:1044–1060. [PubMed: 15669910]
- Hansen BC, Hess RF. Discrimination of amplitude spectrum slope in the fovea and parafovea and the local amplitude distributions of natural scene imagery. *Journal of Vision*. 2006; 6:696–711. [PubMed: 16895453]
- Hebb, DO. *The organization of behavior*. Wiley; New York: 1949.
- Heeger DJ, Bergen JR. Pyramid-based texture analysis/synthesis. *Proceedings of the 22nd Annual Conference on Computer Graphics & Interactive Techniques*. 1995; 30:229–238.
- de Heering A, de Liedekerke C, Deboni M, Rossion B. The role of experience during childhood in shaping the other-race effect. *Developmental Science*. 2010; 13:181–187. [PubMed: 20121874]
- Kelly DJ, Quinn PC, Slater AM, Lee K, Ge L, Pascalis O. The other-race effect develops during infancy: Evidence of perceptual narrowing. *Psychological Science*. 2007; 18:1084–1089. [PubMed: 18031416]
- Kelly DJ, Quinn PC, Slater AM, Lee K, Gibson A, Smith M, Pascalis O. Three-month-olds, but not newborns, prefer own-race faces. *Developmental Science*. 2005; 8:F31–F36. [PubMed: 16246233]
- Kersten D. Predictability and redundancy of natural images. *Journal of the Optical Society of America (A)*. 1987; 4:2395–2400.
- Knill D, Field D, Kersten D. Human discrimination of fractal images. *Journal of the Optical Society of America (A)*. 1990; 7:1113–1123.

- Lewkowicz DJ, Ghazanfar AA. The emergence of multisensory systems through perceptual narrowing. *Trends in Cognitive Sciences*. 2009; 13:470–478. [PubMed: 19748305]
- Oliva A, Torralba A. Modeling the shape of the scene: A holistic representation of the spatial envelope. *International Journal of Computer Vision*. 2001; 42:145–175.
- Olshausen B, Field D. Natural image statistics and efficient coding. *Network*. 1996; 7:333–339. [PubMed: 16754394]
- Pascalis O, de Haan M, Nelson CA. Is face processing species-specific during the first year of life. *Science*. 2002; 296:1321–1323. [PubMed: 12016317]
- Pei F, Pettet MW, Norcia AM. Sensitivity and configuration-specificity of orientation-defined texture processing in infants and adults. *Vision Research*. 2007; 47:338–348. [PubMed: 17188321]
- Portilla J, Simoncelli E. A parametric texture model based on joint statistics of complex wavelet coefficients. *International Journal of Computer Vision*. 2000; 40:49–71.
- Rosenholtz R, Huang J, Raj A, Balas BJ, Ilie L. A summary statistic representation in peripheral vision explains visual search. *Journal of Vision*. 2012; 12(14):1–17.
- Ruderman BL, Bialek W. Statistics of natural images: Scaling in the woods. *Physical Review Letters*. 1994; 73:814–817. [PubMed: 10057546]
- Scott LS, Monesson A. Experience-dependent neural specialization during infancy. *Neuropsychologia*. 2010; 48:1857–1861. [PubMed: 20153343]
- Scott LS, Pascalis O, Nelson CA. A domain-general theory of the development of perceptual discrimination. *Current Directions in Psychological Science*. 2007; 16:197–201. [PubMed: 21132090]
- Sharan L, Li Y, Motoyoshi I, Nishida S, Adelson EH. Image statistics for surface reflectance perception. *Journal of the Optical Society of America*. 2008; 25:846–864. [PubMed: 18382484]
- Simoncelli EP, Olshausen BA. Natural image statistics and neural representation. *Annual Review of Psychology*. 2001; 24:1193–1216.
- Smith LB, Yu C, Pereira AF. Not your mother's view: The dynamics of toddler visual experience. *Developmental Science*. 2010; 14:9–17. [PubMed: 21159083]
- Tadmor Y, Tolhurst D. Discrimination of changes in the second-order statistics of natural and synthetic images. *Vision Research*. 1994; 34:541–554. [PubMed: 8303837]
- Torralba A, Oliva A. Statistics of natural image categories. *Network*. 2003; 14:391–412. [PubMed: 12938764]
- Van der Schaaf A, van Hateren JH. Modeling the power spectra of natural images: Statistics and information. *Vision Research*. 1996; 36:2759–2770. [PubMed: 8917763]
- Yonas A, Granrud CE, Arterberry ME, Hanson BL. Infants' distance perception from linear perspective and texture gradients. *Infant Behavior and Development*. 1996; 9:247–256.
- Yoshida H, Smith LB. What's in view for toddlers? Using a head camera to study visual experience. *Infancy*. 2008; 13:229–248. [PubMed: 20585411]

Figure 1.

The full set of stimuli used in our task. Each column depicts the textures generated from a single original texture. The top half of the figure depicts images in positive contrast and the bottom half depicts images in negative contrast. The bottom row in each half depicts the synthesized versions of the original textures directly above. Synthetic images were matched to the original image for a range of pixel and wavelet statistics, including a final histogram-matching step.

Figure 2.

The average proportion of trials in which infants in each age group preferred the original texture image in the positive and negative contrast conditions. Error bars represent ± 1 standard error of the mean.