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Publication Date
2020-05-01

DOI
10.1016/j.jecp.2019.104772

Peer reviewed

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HHS Public Access
Author manuscript
J Exp Child Psychol. Author manuscript; available in PMC 2021 May 01.

Published in final edited form as:
J Exp Child Psychol. 2020 May ; 193: 104772. doi:10.1016/j.jecp.2019.104772.

Specificity of representations in infants' visual statistical learning

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Abstract

Past work has demonstrated infants' robust statistical learning across visual and auditory modalities. However, the specificity of representations produced via visual statistical learning has not been fully explored. The present study addressed this by investigating infants' abilities to identify previously learned object sequences when some object features (e.g., shape, face) aligned with prior learning and other features did not. Experiment 1 replicated past work demonstrating that infants can learn statistical regularities across sequentially presented objects and extended this finding to 16-month-olds. In Experiment 2, infants viewed test sequences in which one object feature had been removed (e.g., face), but the other feature (e.g., shape) was maintained, resulting in failure to identify familiar sequences. We further probed learning specificity by assessing infants' recognition of sequences when one feature was altered, rather than removed (Experiment 3), and when one feature was uncorrelated with the original sequence structure (Experiment 4). In both cases, infants failed to identify sequences in which object features were not identical between learning and test. These findings suggest that infants are limited in their ability to generalize the statistical structure of an object sequence when the objects' features do not align between learning and test.

Keywords

visual statistical learning; object processing; generalization

As infants observe the world, they are confronted with a nearly continuous stream of visual information. Tracking regularities in this rich input helps infants identify properties of objects (Wu, Gopnik, Richardson, & Kirkham, 2011), form categories (French, Mareschal,

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Declarations of interest: none

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Mermillod, & Quinn, 2004; Sloutsky & Robinson, 2013), learn about the faces of their caregivers (Ferguson, Kulkofsky, Cashon, & Casasola, 2009; Gaither, Pauker, & Johnson, 2012), and begin to disambiguate the meanings of words (Smith & Yu, 2008), among many other feats. Given the ubiquity and significance of visual information surrounding an infant, it is not surprising that infants can track patterns in visual input in the form of conditional statistics, similar to those available in the auditory domain (Saffran, Aslin, & Newport, 1996). Past work has demonstrated that infants can detect the statistical structure of visual information in the form of contingencies between elements in a scene (Fiser & Aslin, 2002) and consistencies in the sequential presentation of objects (Bulf, Johnson, & Valenza, 2011; Kirkham, Slemmer, & Johnson, 2002; Kirkham, Slemmer, Richardson, & Johnson, 2007; Marcovitch & Lewkowicz, 2009; Slone & Johnson, 2015; Stahl, Romberg, Roseberry, Golinkoff, & Hirsh-Pasek, 2014; Tummeltshammer, Amso, French, & Kirkham, 2017). Although research has demonstrated that infants have impressive skills for detecting visual conditional statistics, there is still an incomplete understanding of the nature of this learning.

In an early test of infants' abilities to detect patterns in sequential visual information, Kirkham et al. (2002) presented 2-, 5-, and 8-month-olds with a stream of colorful shapes that formed consistent shape pairs, analogous to the bi-syllabic words used in some investigations of statistical learning in the auditory domain (Antovich & Graf Estes, 2018; Graf Estes, 2012; Graf Estes, Gluck, & Bastos, 2015; Lew-Williams & Saffran, 2012). After habituating to a continuous object sequence, infants viewed sequences of object pairs that were consistent with exposure during learning, or random sequences of objects that violated the pair structure. Infants reliably discriminated between the random and structured sequences, indicating that they had learned the underlying statistical structure of the object sequence. Subsequent work has found that infants may possess the ability to track object co-occurrence patterns even from birth (see also Bulf et al., 2011; reviewed in Krogh, Vlach, & Johnson, 2013), suggesting that infants may be particularly sensitive to this form of statistical information in the visual world.

Although evidence indicates that statistical regularities in the visual modality are accessible even to very young infants, little is known about the representations that underlie visual statistical learning. We do not yet know precisely what information infants encode and store about the elements within a sequence. There is recent evidence that infants store reliable visual sequences (i.e., a series of shapes) as cohesive units or "chunks." Slone and Johnson (2018) found that, after exposure to shape sequences, 8-month-olds differentiated sequences that occurred with high probability in the stream from sequences that partially overlapped with the high probability sequences but did not form complete units. Their findings indicate that infants extract and store detailed information about the patterns of co-occurrence of the elements they observe and use this information to detect coherent units via statistical learning.

There is still a great deal to learn about the information infants encode, store, and apply from statistical learning experiences. The form of the representations that emerge from visual statistical learning is important, because it may influence infants' processing of visual events in their environment. For instance, an infant may view a dinner routine in which plates, cups, and utensils are brought out, then food is served. Learning the properties of the set of objects

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involved may help the infant understand and anticipate aspects of the routine. However, some object features may change across events (e.g., plates can be many colors and sizes, cups vary in height and material), while other features remain consistent (plates are mostly flat and round, cups are generally cylindrical). Thus, the ability to detect the set of features most relevant to the underlying sequence, and to ignore superfluous features, may affect infants' abilities to generalize learning and identify broader routines.

Work by Kirkham et al. (2007) suggests that infants can use multiple feature dimensions to encode and recognize consistent object sequences. Kirkham and colleagues examined spatiotemporal visual statistical learning in infancy, finding that 11-month-old infants learned a sequence of locations for object pairs even when the objects were identical in color and shape. Eight-month-old infants required objects to have unique shapes and colors in order to detect changes in the sequence of object locations, whereas the youngest infants, 5-month-olds, only differentiated between familiar and violation sequences when all three features had changed. This suggests that infants as young as 5 months of age can use correlated features (e.g., color, shape, location) to learn the order of elements within a sequence and that older infants may require fewer redundant cues to identify these sequences. Similarly, Bertels, San Anton, Gebuis, and Destrebecqz (2017) found that infants between 8 and 12 months of age were able to use object location, color, and shape information to encode associations between the layout of a scene and the location of a target object. The work by Bertels et al. (2017) also suggests that infants relied on particular combinations of objects and locations to process the target-context pairings. This supports the role of local learning over global learning, as infants relied on only a portion of the object-based information available in a scene to identify regularities. The present work will expand our understanding of the development of feature use in visual statistical learning by testing 16-month-old infants' use of correlated features to learn and generalize regularities in a continuous stream of objects.

Related work by Turk-Browne, Isola, Scholl, and Treat (2008) has established that adult statistical learning functions over whole objects when features are correlated and over individual perceptual features when some features are irrelevant to learning the underlying object sequences. In the study, participants saw a stream of objects that differed from each other in both shape and color. Similar to Kirkham et al. (2002), objects were presented in consistent combinations (triplets, in this case), with one object appearing on the screen at a time. At test, participants were asked to discriminate between consistent object triplets and random foils. Participants identified the previously seen sequences at greater than chance rates when the objects at test were identical to those seen during the learning phase. However, a series of experiments revealed that, despite initially learning the triplet structure, performance was diminished when participants viewed stimuli that removed some perceptual features of the objects at test (e.g., colorful shapes during training became monochromatic black shapes or identically-shaped color swatches at test). Participants were also less successful at identifying target sequences when the objects' colors at test mismatched colors seen during the learning phase. This suggests that changing features between learning to testing presented a challenge. It inhibited adults' recognition of the trained sequence, but their learning was still sufficiently flexible to recognize the altered objects in their original sequences at levels that exceeded chance performance. Moreover,

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participants' recognition improved if color and shape failed to co-vary perfectly during learning. Specifically, when some objects appeared with a consistent shape, but variable color, during learning (the square was sometimes red, sometimes blue, sometimes green), participants' recognition of the sequences was no longer disrupted by removing the color feature at test. This work suggests that adult visual statistical learning can occur over holistic objects or individual object features (e.g., shape), depending on how closely correlated the objects' features are. Adults' visual statistical learning adjusts to match the learning environment.

The present series of experiments investigated whether infant visual statistical learning can generalize to novel stimuli in which features have changed. Furthermore, we test whether infant learning can adjust in response to variability in the input, similar to adults' flexible visual statistical learning (Turk-Browne et al., 2008). First, we replicated past work demonstrating that infants can track statistical regularities in visual sequences of shape-and-color-based objects. Subsequent experiments examined whether infant statistical learning relies on precise object representations or more abstract, generalizable representations and whether the distinction is related to feature variability during learning.

The object processing literature suggests that infants use features such as shape, pattern, and color to individuate objects by the end of their first year (Wilcox, 1999; Wilcox & Chapa, 2004) and that infants form cohesive object representations based on visual feature co-occurrences (Barry, Graf Estes, & Rivera, 2015; Best, Yim, & Sloutsky, 2013; Fiser & Aslin, 2002; Wu et al., 2011). Thus, infants may track object co-occurrences by using correlated features to identify individual objects. If so, infants' generalization of sequences acquired via visual statistical learning would be constrained by the presence of the co-occurring features. Alternatively, given that infants are able to detect consistent correlations among object features (Younger, 1990; Younger & Cohen, 1983), they may also be able to learn individual feature co-occurrences across objects (e.g., blue before red before green). If infants track multiple feature sequences simultaneously, this could allow them to generalize what they have learned to novel contexts, even when some features present during learning are absent or changed at test. The present research addresses whether infants can generalize the structure of visual sequences to novel stimuli that share some, but not all, perceptual features with their original learning experience. Importantly, this differs from past literature examining rule learning using visual sequences. For example, in work from Saffran, Pollak, Seibel, and Shkolnik (2007), 7-month-old infants were presented with sequences of animals that followed ABB or ABA patterns. The authors found that infants could detect the ABA and ABB patterns when presented with many different sequences exemplifying a single pattern, prompting infants to acquire abstract rules that readily generalize across objects (see also Johnson et al., 2009). Infants in rule-learning tasks have also shown generalization across stimulus types (i.e., spoken ABB patterns recognized in nonspeech sounds; Marcus, Fernandes, & Johnson, 2007) following exposure to multiple examples of a pattern. On the other hand, the present work presented infants with consistent objects in consistent sequences, which may hinder, rather than promote, generalization.

Although infants' abilities to generalize statistical representations in the visual modality have not been assessed, analogous research in the auditory modality suggests that infants can

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generalize the output of auditory statistical learning to novel circumstances (e.g., new speaker voice; Graf Estes, 2012) and that increased variability during learning may enhance this flexibility (Graf Estes & Lew-Williams, 2015). Thus, it is possible that infants may recognize previously learned visual sequences even when features of these objects have been altered. However, given adults' difficulty identifying previously viewed sequences when consistently co-occurring perceptual features changed between learning and recall (e.g., Turk-Browne et al., 2008), we predicted that infants would only demonstrate statistical learning when test conditions closely aligned with conditions present during learning.

Experiment 1

Experiment 1 was designed to replicate and build on past work demonstrating that infants readily track transitional probabilities in sequences of visual objects (e.g., Kirkham et al., 2002). During habituation, infants viewed a series of colorful shapes with a unique face superimposed on each object. Introducing faces to the colorful shapes allowed us to include a salient dimension to manipulate in Experiments 2–4. There is ample evidence that infants are highly attentive to faces (e.g., Frank, Vul, & Johnson, 2009); therefore they are likely to attend to this feature along with the shape and color dimensions during learning. At test, we assessed whether infant looking time discriminated between sequences that were consistent with those learned during habituation and sequences that violated prior learning.

Method

Participants.—Twenty-two 16-month-old infants (*M* = 16 months, 8 days; Range = 15 months, 12 days – 16 months, 25 days) participated in Experiment 1. Previous research has focused on young infants (newborns, Bulf et al., 2011; 2- to 8-month-olds, Kirkham et al., 2002; Slone & Johnson, 2015), and there has been some recent research with older children (e.g., 5- to 12-year-olds, Bertels, Boursain, Destrebecqz, & Gaillard, 2015; Raviv & Arnon, 2017). The present study expands this work to test older infants, who are presumably capable of more advanced visual pattern learning and generalization than very young infants (e.g., Kirkham et al. 2007; see Krogh, Vlach, & Johnson, 2013 for discussion of the development of statistical learning abilities). Thus, selecting participants from an older range than in prior work fills in a gap in our understanding of the developmental timeline of visual statistical learning and may increase the likelihood of successful generalization in Experiments 2–4, in which object features change between learning and test.

Across Experiments 1–4, infants had no history of known visual impairments and were born full-term. Infants primarily came from English-speaking households. In Experiment 1, seven infants heard a second language (up to 16 hours per week), assessed via parent report. Additional infants were excluded from analyses because of fussiness or crying (10) or moving out of the video frame (2). For each experiment, before performing the full analyses, we examined the data for outliers based on looking-time difference scores (to violation versus consistent test trials) greater than 2 *SD* from the mean. No infants met this criterion.

Stimuli.—During the habituation phase, infants viewed silent videos presenting a series of twelve colorful shapes superimposed with cartoon faces (see Figure 1). The objects appeared one-by-one on a white screen, loomed for 1 s until doubled in size, reaching approximately

6” x 6” (9.6° x 9.6° at a viewing distance of 36”), then disappeared. The object sequence comprised repetitions of four consistent shape[1] triplets. These triplets were then pseudo-randomized with the constraint that no object triplet could occur twice in a row. Thus, the transitional probability from one object to the next within each triplet was 1.00 and the average transitional probabilities across triplets was 0.33 (range 0.26 – 0.38). We created 21 videos for the habituation trials, each presenting a different randomization of the triplet sequences. The presentation order of the habituation videos was randomized.

After habituation, infants completed test trials to assess learning. Half of the test trials consisted of sequences that maintained the original object triplets, and half were randomized sequences. *Consistent sequences* had a statistical structure that aligned with the sequences viewed during habituation and included the same four object triplets presented in a pseudo-random order. There were four consistent sequence test trials with different pseudo-randomized orders of the triplets, with the constraint that no triplet occurred twice in a row. *Violation sequences* were inconsistent with the order of objects seen during habituation. In these trials, the 12 individual objects were presented in a pseudo-random order, with the constraint that objects were not repeated twice in succession. Across the four violation sequence test trials, infants saw four different randomizations of the 12 shapes. The shapes for each experiment were created, animated, and edited using Microsoft PowerPoint, Adobe Photoshop, Adobe Director, and FinalCut Pro.

Procedure.—Infants completed habituation and testing in a small, sound-attenuated booth. Throughout testing, infants sat on a parent’s lap facing a large television monitor used to display stimuli at infant eye-level. Parents were discouraged from directing the infant’s attention while stimuli were playing and were monitored for interference. Additionally, parents wore headphones playing classical music during the experiment to reduce the likelihood of infant-parent interaction. During habituation, infants viewed the object sequences described above. After each trial, infants saw an attention-getting video of a rotating pinwheel accompanied by music. The order in which the habituation videos were presented was randomized. Each habituation trial ended when the infant looked for a minimum of 2 s and looked away for at least 1 s or after 20 s had elapsed. The habituation phase ended once an infant’s average looking time across three consecutive trials fell below 50% of his or her average looking time during the first three habituation trials or after a total of 21 trials. Test trials began immediately after habituation trials. The eight test trials (four consistent and four violation test sequences) were presented in random order. If infants acquired the statistical structure of the visual stream during habituation, we expected them to attend longer to the test sequences that violated prior learning than to sequences that aligned with it. The experiment was conducted using Habit 2 software (Oakes, Sperka, & Cantrell, 2015). Experimenters coded infant looking behavior online using keypresses while watching a video feed of the testing booth from a separate room. Experimenters were unaware of trial type.

[1]We use the term “shape” to refer to the two-dimensional geometric shapes and their associated colors. These features co-occurred consistently.

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Results and Discussion

Table 1 shows infants' time and number of trials to reach the habituation criterion for Experiments 1–4. As reported in Table 1, a multivariate ANOVA revealed that there were no significant differences in habituation time or number of trials to reach habituation across experiments, $F(4, 107) = 0.36$, $p = .83$, $\eta_p^2 = 0.01$.

A two-tailed, paired samples *t* test comparing infants' average looking time toward consistent and violation sequences revealed that infants looked longer during the violation sequences, $t(21) = -2.61$, $p = .016$, $d_z = -0.55$ (see Table 2). To illustrate the range of infants' performance, Figure 2 presents looking-time data for each infant using the looking-time difference scores (looking time on violation – consistent test trials). This finding shows that 16-month-old infants detect statistical regularities present in visual sequences, in line with work by Kirkham et al. (2002). With infants' learning pattern for the object sequences established, subsequent experiments investigated infants' abilities to recall previously learned object sequences under changed circumstances.

To support interpretation of the findings, we also calculated Bayes factors (Rouder, Speckman, Sun, Morey, & Iverson, 2009; Wagenmakers et al., 2018). In contrast with null hypothesis testing methods, Bayes factors allow for a comparison of the strength of support for the null hypothesis and the alternative hypothesis. In other words, we can quantify evidence in favor of the absence of an effect (i.e., the null hypothesis) and the evidence in favor of the presence of an effect (i.e., the alternative hypothesis). For all experiments, we used the calculator by Rouder et al. (2009) and the recommended JZS Bayes Factor value, which is not based on prior expectations of effect sizes. The estimated Bayes factor indicated that the hypothesis that infants' looking times to violation versus consistent sequences were *different* was 3.3 times more likely than the null hypothesis of no difference, a substantial effect (Jeffreys, 1961).

Experiment 2

Experiments 2 through 4 built on the findings of Experiment 1 to explore the conditions under which infants recognize previously viewed sequences. We investigated whether infants can recognize familiar visual sequences when salient features of those sequences are removed or altered during testing. In Experiment 2, we tested infants' recognition of the object sequences described in Experiment 1 when either the face or shape feature was removed. During learning, these features provided redundant cues to the statistical structure of the sequence. Here, we addressed whether infants require the presence of both of these correlated cues at test to recognize the structures they learned.

Method

Participants.—Forty-five 16-month-old infants (*M* = 16 months, 17 days; Range = 16 months, 3 days – 17 months, 0 days) participated in Experiment 2. Infants came from the same population described in Experiment 1. All infants primarily heard English, and 10 infants also heard a second language (up to 16 hours per week), per parent report. Additional infants were excluded from analyses for fussiness or crying (Shape condition: 13; Face

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condition: 12), moving out of the frame (Face: 1), parental interference (Face: 1), falling asleep (Shape: 1), and equipment error (Shape: 1).

Stimuli.—The object streams presented during habituation were identical to those from the habituation phase of Experiment 1. As in Experiment 1, infants viewed object sequences at test that were consistent with the statistical structure from habituation sequences (consistent trials) and sequences that violated prior learning (violation trials). Evidence from Experiment 1 suggests that infants can readily discriminate between these two trial types when all of the objects' features are consistent between habituation and test. However, in Experiment 2, infants viewed test stimuli in which features of the objects had been removed from the stream. In the Shape condition, infants viewed test sequences in which the object shape and color were maintained, but the object was no longer superimposed with a cartoon face (see Figure 1). In the Face condition, test sequences only retained the faces from habituation, without any background shape or color (see Figure 1). Thus, during habituation the faces and shapes were perfectly correlated, as in Experiment 1, but at test salient features were removed. In both conditions, infants viewed consistent sequences that aligned with learning (but were missing a feature) and violation sequences in which a feature was missing and the objects were presented in a novel, randomized order.

Procedure.—The procedure was the same as in Experiment 1, with the exception that during testing, one group of infants (n = 23) viewed test sequences from the Shape condition and another group viewed test sequences from the Face condition (n = 22). If infants recognized previously seen sequences at test, despite the removal of one of the objects' features, we expected infant looking time to differentiate between consistent and violation sequences. However, if removing a feature at test disrupted infants' recognition of the sequences, infant looking time should not differentiate between consistent and violation sequences.

Results and Discussion

Table 1 shows infants' time and number of trials to reach habituation. We conducted a two (Condition: Face vs. Shape; between subjects) x two (Trial type: consistent vs. violation; within subjects) mixed ANOVA to determine whether infants' looking time discriminated between consistent and violation sequences at test and whether this discrimination differed across the two conditions. There were no significant main effects or interactions, suggesting that infants did not reliably discriminate between consistent and violation sequence test trials in either condition, nor did overall looking time differ across conditions, *F*s $(1, 43) < 0.94$, *p*s $> .34$, $\eta_p^2 < 0.02$ (see Table 2 and Figure 2). It is possible that infants' abilities to discriminate between sequences of shapes or faces that aligned with or violated prior learning were impaired when a feature of the object was removed.

Although the interaction was not significant, given the visual salience of faces, we analyzed the data separately for the face-only and shape-only test conditions. In the Face condition, there was no difference in looking time to consistent versus violation sequences, $t(21) = 0.022$, $p = .983$, $d_z = 0.004$. In the Shape condition, there was also no difference, $t(22) = 0.444$, $p = .662$, $d_z = 0.093$. The Bayes factor analysis was consistent with the *t* tests,

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providing further support for the null hypothesis. The Bayes factors indicated that the hypothesis that looking times did not differ was 4.5 times more likely than the alternative hypothesis of different looking times for the Face condition and 4.18 times more likely in the Shape condition, both substantial effects (Jeffreys, 1961). Thus, the Bayes factor analyses support the conclusion that infants did not demonstrate recognition of the violation versus consistent test trials.

We also considered the possibility that, because all of the test items were new (i.e., consistent and violation sequences had a missing dimension, face or shape), the novelty of the test items could have superseded infants' attention to the sequence-level novelty of the violation test sequences. To test this idea, we examined infants' performance separately for the initial and final sets of familiar and novel trials. We compared performance in the first two consistent versus first two violation trials then compared the last two instances of each trial type. Because the trials were randomized, these analyses did not always split the first four versus last four test trials in sequence, but each comparison included an equivalent number of each trial type. We hypothesized that if the initial novelty of the altered stimuli overwhelmed infants' differentiation of the two trial types, discrimination may be apparent only in the latter portion of testing. Infants did not show a significant difference in looking time to the violation trials in the first set of trials, $t(44) = 0.332$, $p = .740$, $d_z = 0.049$, or in the second set of trials, $t(44) = -0.010$, $p = .992$, $d_z = -0.001$. Infants did not differentiate the violation and consistent test items as they became more familiar with them. We cannot rule out the possibility that the change in appearance of the test items affected performance. Rather, we propose that recognizing the consistent sequence across change is an important part of generalization and infants have not displayed successful generalization under these conditions.

The use of faces in the present stimuli may have affected infants' learning. Faces are known to have privileged status for infants (Frank et al., 2009; Valenza, Simion, Cassia, & Umiltà, 1996). Although statistical learning is thought to be implicit, attentional resources are still necessary to capture the appropriate input (Toro, Sinnett, & Soto-Faraco, 2005). The attention-grabbing presence (and subsequent conspicuous absence) of faces could have affected how infants processed the shape sequence during learning and testing. Infants may have primarily attended to the sequence of faces, ignoring information provided by the background shapes, which could inhibit recognition of the shape sequences at test. However, as described above, we did not observe learning differences between the Shape and Face conditions of Experiment 2 or habituation differences between experiments. Thus, it is unlikely that the manipulation of face features specifically (in contrast with another salient feature, shape) can fully account for the observed effects.

During learning, the manipulated features (i.e., faces and shape) covaried perfectly, as each shape was superimposed with a consistent and unique cartoon face. At test, the contingency between shape and face could not be used to support recognition of previously viewed sequences. Work on object processing has suggested that across the first year of life, infants are increasingly able to use features such as shape, pattern, and color to individuate objects (Wilcox, 1999; Wilcox & Chapa, 2004) and that infants form holistic object representations via co-occurring features (Wu et al., 2011). Thus, when infants learn sequences in which object features are correlated, it may be difficult for infants to recognize the same statistical regularities when only a subset of object features is present at test.

It is also possible that infants' recognition of the object sequence structure was disrupted by the visual disparity between objects presented during learning versus at test. Seeing shapes with no faces and faces with no shapes may have prevented infants from generalizing their prior experience with the object sequences. If the test items were more holistically similar to learning (i.e., colorful shapes with superimposed faces), infants may recognize the consistent sequences even when test items are not identical to those viewed during learning (i.e., face-shape pairings differ between learning and test).

Experiment 3

Experiment 3 investigated the specificity of infants' statistical representations by assessing whether infants would generalize the statistical structure of previously viewed object sequences to novel, but visually similar, stimuli. The structure of the task was comparable to Experiment 2; infants viewed the same sequences of shapes paired with consistent faces during the learning phase. During testing, infants viewed test trials that had shapes with superimposed faces but the face-shape combinations were pseudo-randomized. That is, at test the shape-face correlations were inconsistent with learning. With this manipulation, the overall appearance of the test items was similar to learning, but the precise feature combinations of the original objects were absent. Salient differences in the color and shape of individual objects may provide enough information for infants to recognize previously viewed sequences when they are coupled with similar, though not identical, face information. This allowed us to test whether infants can generalize visual statistical learning across a change in object feature combinations. If infants learn the sequence regularities separately for individual features (i.e., shape and face), their prior experience could support recognition of the previously viewed shape sequences even when the face feature is no longer informative.

Method

Participants.—Twenty-three 16-month-old infants (*M* = 16 months, 16 days; Range = 16 months, 0 days – 16 months, 28 days) participated in Experiment 3. Infants came from the same population described in Experiment 1. All infants primarily heard English, and six infants also heard a second language (up to 16 hours per week), per parent report. Additional infants were excluded from analyses for fussiness or crying (17), equipment error (2), and distraction (1).

Stimuli.—The object streams presented during the habituation were identical to those in Experiment 1. At test, infants viewed streams of objects in which the shape sequences were either consistent with the habituation sequences (consistent trials) or violated past learning (violation trials). However, in Experiment 3, the shape-face contingencies that were present during learning were eliminated at test. The face sequence was pseudo-randomized so that each shape appeared with several different faces. The constraints on the face pseudo-randomization were that no face occurred twice in succession and that some shape + face pairs were not possible due to the shapes' dimensions. Each shape appeared with at least

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three different faces (see Figure 1). Thus, the test objects were broadly visually similar to objects viewed during habituation (i.e., they consisted of shapes with superimposed faces) but test sequence objects used novel shape + face pairs.

Procedure.—The procedure was identical to Experiment 1.

Results and Discussion

Infants' number of trials and time to habituation are shown in Table 1. A two-tailed, paired samples *t* test comparing infants' average looking time toward consistent versus violation test sequences revealed that infants did not reliably discriminate between trial types, $t(22) = -0.12$, $p = .90$, $d_z = -0.02$ (see Table 2 and Figure 2). Thus, infants provided no evidence that they recognized the previously encountered object triplets at test when the pattern presented by one feature of the objects (faces) mismatched the information encountered during learning. The Bayes factor analysis indicated that the hypothesis that looking times did not differ was 4.5 times more likely than the alternative hypothesis that looking times differed. This analysis supports the notion that infants treated the violation and consistent test items similarly.

As in Experiment 2, we also examined infants' looking time in the first two consistent trials versus the first two violation trials and did the same for the final consistent and violation trials. In the first set of trials, infants looked marginally longer to the consistent sequence than the violation sequence, $t(22) = -1.89$, $p = .072$, $d_z = -0.394$. In the second set of trials, infants looked marginally longer at the violation sequence $t(22) = 1.77$, $p = .090$, $d_z = 0.369$. These patterns did not reach the threshold for significance, so we must be cautious in their interpretation. There are several reasons why infants' pattern of preference may have shifted over the course of testing. It is possible that, in the early trials, infants detected the similarity of the consistent shape sequence, or the mismatch of the shape sequence with the randomized faces, which initially drew their attention. By the end of the test trials, attention shifted toward the novelty of the violation sequences. Alternatively, infants may have used exposure to the consistent test sequences to gather additional experience with the shape sequences that were encountered during learning, promoting a shift in attention toward the novelty of the violation sequences by the end of testing. A third possibility is that because the violation and consistent test trials both included face sequence violations, infants treated the test trial types as equivalent (though the Face condition of Experiment 2 suggests this might not be the case). It is also possible that the looking pattern represents random changes in attention over the course of eight test trials. These are interesting hypotheses that require additional experiments to pull apart and are beyond the scope of the present investigation. However, what we have demonstrated is that "filling in" the shapes with a different sequence of faces did not yield robust generalization, which would be demonstrated by longer looking at the violation test sequence, as in Experiment 1.

Thus, both Experiments 2 and 3 suggest that infants' abilities to generalize statistical relationships in the visual modality are limited, at least in the present paradigm. In comparison with learning demonstrated in Experiment 1, infants' overall looking patterns in Experiments 2 and 3 suggest that they had difficulty detecting the consistent statistical

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structure shared across learning and test sequences or were unable to express their learning, when features of the objects were altered. Based on prior work with adults (Turk-Browne et al., 2008), we hypothesized that the consistent face-shape pairings presented during the learning phase led infants to develop precise representations of the objects, which then impaired subsequent performance at test when the objects were changed (Oakes, Coppage, & Dingel, 1997). In other words, the invariable feature pairings seen during learning may have prevented infants from forming more abstract, generalizable representations. In this case, infants' generalization may improve if the object sequences presented during learning exhibited greater feature variability, highlighting sequence-relevant and irrelevant features. Experiment 4 investigated this possibility.

Experiment 4

Experiment 4 explored whether increased feature variability during learning would allow infants to generalize previously encountered statistical regularities. Infants viewed streams of shape triplets that had superimposed faces, but the faces did not co-vary with shape during learning or present a reliable pattern on their own. We then tested whether infants could recognize the shape sequences without faces (as in Experiment 2) after training with objects that maintained consistent shape triplets but had variable faces. Thus, the faces were uninformative for learning or recognizing the shape sequences.

Method

Participants.—Twenty-two 16-month-old infants (*M* = 16 months, 19 days; Range = 16 months, 0 days – 17 months, 0 days) participated in Experiment 4. Infants came from the same population described in Experiment 1. Most infants primarily heard English, with nine infants also exposed to a second language (up to 16 hours per week) per parent report. One additional infant was primarily exposed to Spanish. The pattern of results was the same with this infant excluded, so the infant was included in the final sample. Additional infants were excluded from analyses for fussiness or crying (11), equipment error (2), and excessive movement (1).

Stimuli.—The object streams presented during the habituation phase maintained the same shape triplet sequences from Experiments 1–3. However, the shapes were no longer paired with consistent superimposed faces. Each token of an individual shape was pseudo-randomly paired with a face during habituation using the same constraints as the test phase in Experiment 3 (see Figure 1). Each shape appeared with a minimum of three faces. The face and shape features of the objects were not correlated during habituation and the faces occurred in a pseudo-random order. Thus, the face information was uninformative for learning the shape sequences, and the faces did not form consistent sequences themselves. At test, infants viewed streams of shapes with a statistical structure that was either consistent with the habituation sequences or that violated past learning; the test items were the same as the Shape condition in Experiment 2 and had no faces.

Procedure.—The procedure was identical to Experiment 1.

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Results and Discussion

Infants' number of trials and time to habituation are shown in Table 1. A two-tailed, paired samples *t* test comparing infants' average looking time toward consistent and violation test trials revealed that infants did not reliably discriminate between trial types, $t(21) = -0.29$, $p = .90$, $d_z = -0.06$ (see Table 2 and Figure 2). The Bayes factor analyses indicated that the hypothesis that looking times did not differ was 4.3 times more likely than the alternative hypothesis of different looking times. This analysis supports the notion that infants treated the violation and consistent test items similarly. Infants displayed no evidence of recognizing the shape sequence, suggesting that variability in the face-shape pairings did not help infants recognize the shape-only sequence.

To test the possibility that the initial novelty of the test items overwhelmed infants' attention, we analyzed the first set of consistent and violation trials separately from the last set of trials. The results were the same in both sets; infants did not differentiate violation and consistent trials in the first set, $t(21) = 0.230$, $p = .752$, $d_z = 0.049$, or second set, $t(21) = 0.144$, $p = .887$, $d_z = 0.031$, of test trials.

This contrasts with the findings from experiments with adults demonstrating that variation in feature combinations during learning allowed adults to track statistical regularities across features, rather than whole objects (Turk-Browne et al., 2008). The findings in the present experiment align with Experiments 2–3, suggesting that infant visual statistical learning does not readily generalize across changes in objects' appearances. However, from this experiment, it is not possible to determine whether infants failed to learn at all when the face and shape cues were uncorrelated. Future experiments will test whether variation in features impedes learning overall or whether infants trained with consistent shape sequences, but variable faces, can recognize the shape sequences when variable faces are also present at test. Regardless, Experiment 4 demonstrates that uncoupling the face-shape pairings does not help infants recognize the shape sequences in isolation.

General Discussion

The findings from this series of experiments suggest that infants' representations of statistically-defined visual sequences are tightly tied to the perceptual details of the input. In Experiment 1, we found that infants learned a visual sequence of colorful shapes with superimposed faces. This result replicates prior demonstrations of robust visual statistical learning of sequences (Kirkham et al., 2002; Marcovitch & Lewkowicz, 2009; Slone & Johnson, 2015) using an older age group and stimuli with more feature dimensions than many previous experiments. Experiment 1 helps to bridge research on early visual statistical learning with the literature investigating visual statistical learning in older children and adults (e.g., Bertels et al., 2015; Raviv & Arnon, 2017; Turk-Browne et al., 2008; Turk-Browne & Scholl, 2009). However, a lack of evidence of learning in Experiments 2–4 suggests that there are limitations to infant visual statistical learning.

When some visual features of the objects changed between learning and test, infants did not appear to recognize the underlying statistical structure that was shared with habituation sequences; they no longer differentiated between consistent and violation test sequences.

This failure to generalize from the original habituation sequences occurred when one feature was absent at test (i.e., faces or shapes, Experiment 2) and when both features were present at test, but only one aligned with prior learning (Experiment 3). Importantly, the stimuli presented during learning sequences in Experiments 1–3 were identical, suggesting that infants' difficulty differentiating the consistent versus violation test sequences in Experiments 2 and 3 was due to the presence of altered object features at test, rather than an underlying failure to learn. Experiment 4 assessed whether additional variability during habituation would promote generalization in statistical learning by providing one relevant feature with a consistent statistical structure across objects (i.e., shape) and one irrelevant feature without this structure (i.e., face). We hypothesized that tracking statistical regularities for the relevant feature would allow infants to generalize learning to sequences in which the irrelevant feature was absent, as was found for adults (Turk-Browne et al., 2008). Contrary to this hypothesis, Experiment 4 demonstrated that training on shape sequences with variable face pairings during learning did not support the formation of more robust, generalizable representations of the shape sequences. Across experiments, infants only demonstrated what they had learned about the visual sequences when the learning and test items matched on all dimensions. Infants' failure to discriminate consistent versus violation sequences in Experiments 2–4 cannot tell us whether infants are incapable of generalizing any form of sequential information acquired via visual statistical learning. However, it does suggest that generalization provides additional challenges, and thus may require additional support (e.g., several redundant cues). This aligns with findings from Kirkham and colleagues (2007) suggesting that multiple correlated features can help infants detect a change in pattern. It is possible that with scaffolding infants may have successfully discriminated between consistent and violation sequences in Experiments 2–4.

One alternative explanation for infants' lack of clear preference in the looking tasks in Experiments 2 and 4 is that the novel appearance of the test items (e.g., via removal of face or shape features) might have overwhelmed infants' attention, causing looking time for both trial types to be at "ceiling" for these stimuli. Thus, a novelty preference for violation test sequences may have been negated by a global increase in infants' attention to test trials, due to the change in form between training and test. However, this alternative explanation seems unlikely, as infant performance was similar in the initial and final sets of test trials. The results of Experiment 3 also support this conclusion because the test trials maintained the overall visual appearance of the objects (colorful shapes superimposed with a variety of cartoon faces), yet infants' looking times still did not reliably differentiate between trial types. Taken together, these findings suggest that the similarity of infants' looking time to consistent and violation sequences was not due to overwhelming novelty of both trial types at test.

Another alternative explanation is introduced in work by Addyman and Mareschal (2013), which found that infants could discriminate between structured and unstructured visual sequences even without prior training. Thus, it is possible that infants in Experiment 1 were simply differentiating between trial types based on local variability. However, if this were the case, we would anticipate similar discrimination at test in Experiments 2–4, as test trials in these experiments had similar structures to trials in Experiment 1 (i.e., ordered triplet sequences versus randomized object sequences). This suggests that test performance in

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Experiment 1 was likely driven by learning during training, rather than the inherently structured or unstructured nature of the test stimuli. To further test the alternative explanation we had a group of infants from the same population described in Experiment 1 complete a control condition in which they viewed test trials identical those in Experiment 1 but without prior training. Infants (n = 22) did not look reliably longer to consistent sequences (i.e., structured, $M = 13.99$ sec, $SD = 3.99$) compared to violation sequences (i.e., unstructured, $M = 13.76$ sec, $SD = 4.32$), $t(21) = 0.300$, $p = .767$, $d_z = 0.064$. This result suggests that infants in Experiment 1 had learned the underlying structure of the sequences during training and relied on this knowledge to discriminate between trial types at test.

Infants' difficulty recognizing the altered visual sequences in Experiments 2–4 aligns with the Extraction and Integration framework of statistical learning (Erickson & Thiessen, 2015; Thiessen, Kronstein, & Hufnagle, 2013) and the notion that infants extract coherent chunks via visual statistical learning (Slone & Johnson, 2018). The Extraction and Integration framework proposes that chunks of consistently co-occurring elements are formed through an iterative process in which memory for consistent sequences strengthens and memory for inconsistent sequences decays due to time or interference. As chunked sequences are reencountered, the alignment of perceptual features between previously encountered and new stimuli matters; if the novel input differs from prior learning, recognition is impaired, due to a weakened memory trace. In the present study, infants successfully recognized previously learned sequences when perceptual features aligned perfectly between learning and test (e.g., Experiment 1) but did not reliably demonstrate recognition of the learned sequences when perceptual features changed between the two experimental phases (Experiments 2–4). This framework suggests that providing fewer correlated features and increasing noise during the learning phase of Experiment 4 may have increased the difficulty of the task, reducing the perceptual features available to support learning. If so, additional training with the variable face stimuli in Experiment 4 may help infants ignore the uninformative variability in face features to detect regularities in the underlying shape triplets.

Differences in training and testing format limit our ability to compare the present infant findings and prior work with adults. Infant testing methods are often limited in their ability to detect fine-grained differences in learning, typically yielding the presence or absence of evidence of learning (i.e., statistically reliable differentiation of two test trial types), rather than graded differences in performance. In contrast, measures of adults' responses can reveal graded differences in accuracy even across conditions that show successful (i.e., above chance) learning. Thus, more sensitive infant testing methods may allow us to better detect generalization. In any case, some limitations on infant learning in the present study were not shared by adults in Turk-Browne et al.'s work (2008), suggesting that visual statistical learning is not a static ability but one that may change over time. Turk-Browne et al. (2008) reported that, for adults, changing the color or shape of items in a sequence moderated participants' performance relative to baseline learning. Like adults, 16-month-olds' expression of learning was affected by a salient feature change. However, infant and adult learners responded differently to variation during learning. For adults, when the features (color and shape) are not tightly coupled during learning, adults can shift to detecting patterns in isolated features (e.g., monochromatic shapes) rather than whole objects. In

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contrast, infants' generalization did not benefit from variation in feature combinations during learning. To further assess this pattern of learning, future work could examine whether infants learn the underlying structure of the object sequences when one feature dimension is uncorrelated and uninformative of the sequence's structure both at learning and at test.

Our results cannot directly address the hypothesis that visual statistical learning abilities develop over time. Nevertheless, differences between infants' performance in the present study and related adult work (Turke-Browne et al., 2008) align with growing evidence that visual statistical learning matures throughout infancy and childhood. Kirkham et al.'s (2007) test of spatiotemporal visual statistical learning showed that older infants could use a single object feature, location, to identify temporal sequences that aligned with prior learning, whereas younger infants required additional supporting perceptual features (i.e., shape and color) to learn the sequences. This suggests that infants' use of perceptual features in visual statistical learning develops across the first year of life. Additionally, Raviv and Arnon (2017) found that performance in a visual statistical learning task improved steadily across middle childhood, demonstrating that visual statistical learning abilities continue to change well beyond infancy.

The present finding that infants failed to generalize in the visual statistical learning task differs from past work on linguistic statistical learning, which has demonstrated that infants can generalize statistical knowledge across changing contexts. Infants can recognize statistically segmented words in a novel voice (Graf Estes, 2012) and detect the underlying statistical structure of speech presented across multiple voices (Graf Estes & Lew-Williams, 2015). It is possible that infants' frequent experience navigating surface-level changes in speech input (e.g., changes in pitch, volume, background noise, etc.) may have prepared them for similar changes instituted in these statistical learning tasks. The visual objects in the present experiment are much less familiar than speech; infants have not had rich experience determining how to interpret the objects or their features (see also Saffran et al., 2007). In this case, infants' attention to detail in the task may be an adaptive learning strategy. The highly novel context of tracking sequences of colorful shapes with faces may elicit a representation that precisely codes all the features of the stimuli. The specificity of this representation may inhibit recognition when the learning probe (feature-altered test items) does not effectively link back to the original highly-specified memory. It would be possible to systematically test the specificity with which infants encoded the stimuli using a change detection task, similar to Ross-Sheehy, Oakes, and Luck (2003). In this case, infants would be presented with visual streams in which object features are altered or remain the same. If infants encoded the object representations with a high level of specificity, they should prefer the changing stream over the unchanging stream. Alternatively, if infants' memories for the objects did not include all discriminating features, they should not distinguish between the two streams.

Our findings suggests that infant visual statistical learning may, at least initially, be constrained by the specific examples infants encounter. From very early in life infants can generalize patterns acquired via visual learning (Ferguson, Franconeri, & Waxman, 2018; Johnson et al., 2009; Saffran et al., 2007). In the present tasks, however, infants are primed to learn a stimulus-specific pattern, rather than a general rule and learning is accomplished over a very short time. Afterward, they face the challenge of recognizing a fragment of a familiar pattern with information missing or even contradicting prior learning. This fundamental difference in the nature of the exposure sequences may drive differences between the present work and prior studies examining rule learning. Moreover, the abstract nature of the stimuli may further hinder generalization. A recent meta-analysis from Rabagliati, Ferguson, and Lew-Williams (2019) suggests that pattern abstraction is easiest for stimuli that are meaningful, with patterns in speech detected more readily than non-speech patterns. Given the novel nature of the present stimuli for infants, additional experience with the objects may have been necessary for infants to successfully generalize learning after changes to key features. Thus, as infants gain experience with series of objects and events in their environments, their abilities to recognize familiar patterns despite surface-level changes may become more robust. To continue an example introduced above, a change in the collection of objects or the sequence of events related to mealtime may be initially difficult to interpret for an infant, but greater familiarity with the sequence and experience with variability in the order and composition of events may promote generalization and support recognition despite surface-level changes.

In conclusion, our findings provide additional evidence that infants can track co-occurrence regularities across visual elements presented sequentially. However, infants' representations of the visual elements appear to be highly specified, leading missing or changed features to impair infants' abilities to recognize previously learned statistical sequences. Of course, the ability to generalize emerges with experience and becomes more robust across development; generalization is essential for applying learning in one situation and extending it to novel events. Future research is needed to investigate which types of experiences (e.g., greater exposure, greater variation in exposure) support successful generalization.

Acknowledgements:

This research was supported by a grant to Katharine Graf Estes from the National Institute of Child Health and Human Development (Grant No. HD062755). We thank parents who generously contributed their time, as well as Jessica Bloom, Rebekah Solomon, Destiny Harriman, Carolina Bastos, Lauren Levenson, Daniela Guarnizo, and the members of the Language Learning Lab at UC Davis for their assistance with this research. Thanks also go to Lauren Slone for helpful comments on an earlier draft of the manuscript.

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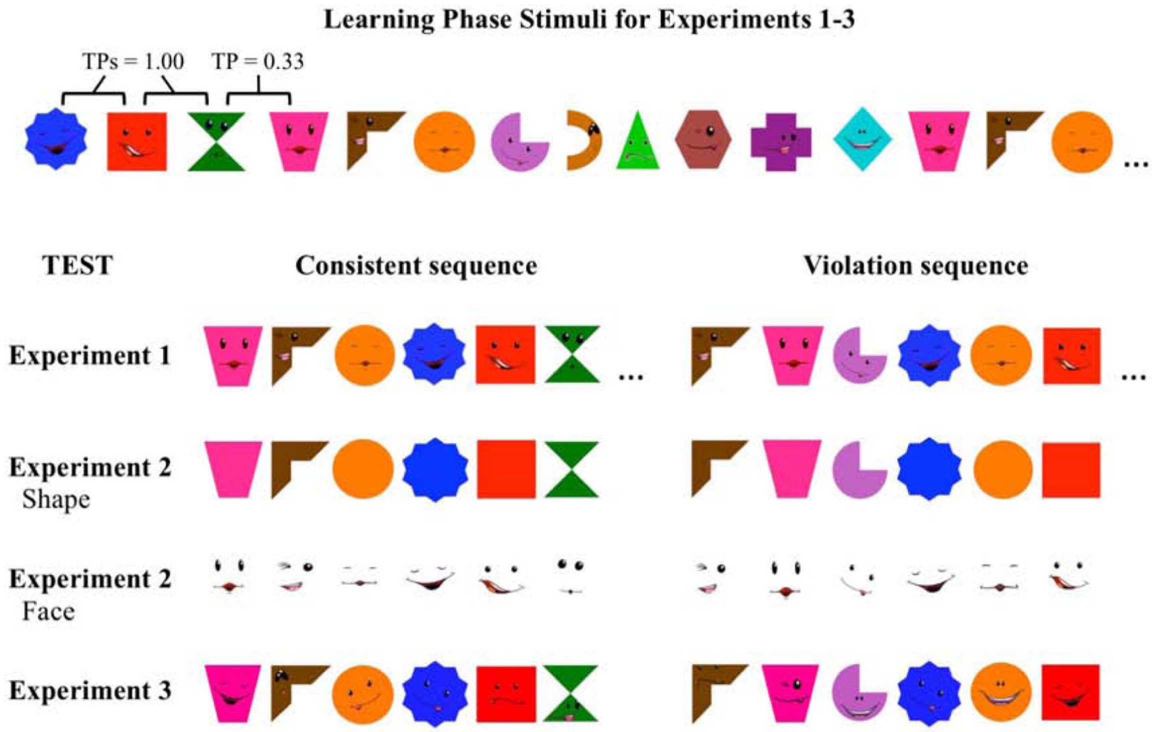

Figure 1.

Example learning and test phase stimuli for Experiments 1–3. Experiment 4 learning phase stimuli were similar to the test stimuli from Experiment 3, and Experiment 4 test stimuli were similar to the test stimuli from the Experiment 2 Shape condition.

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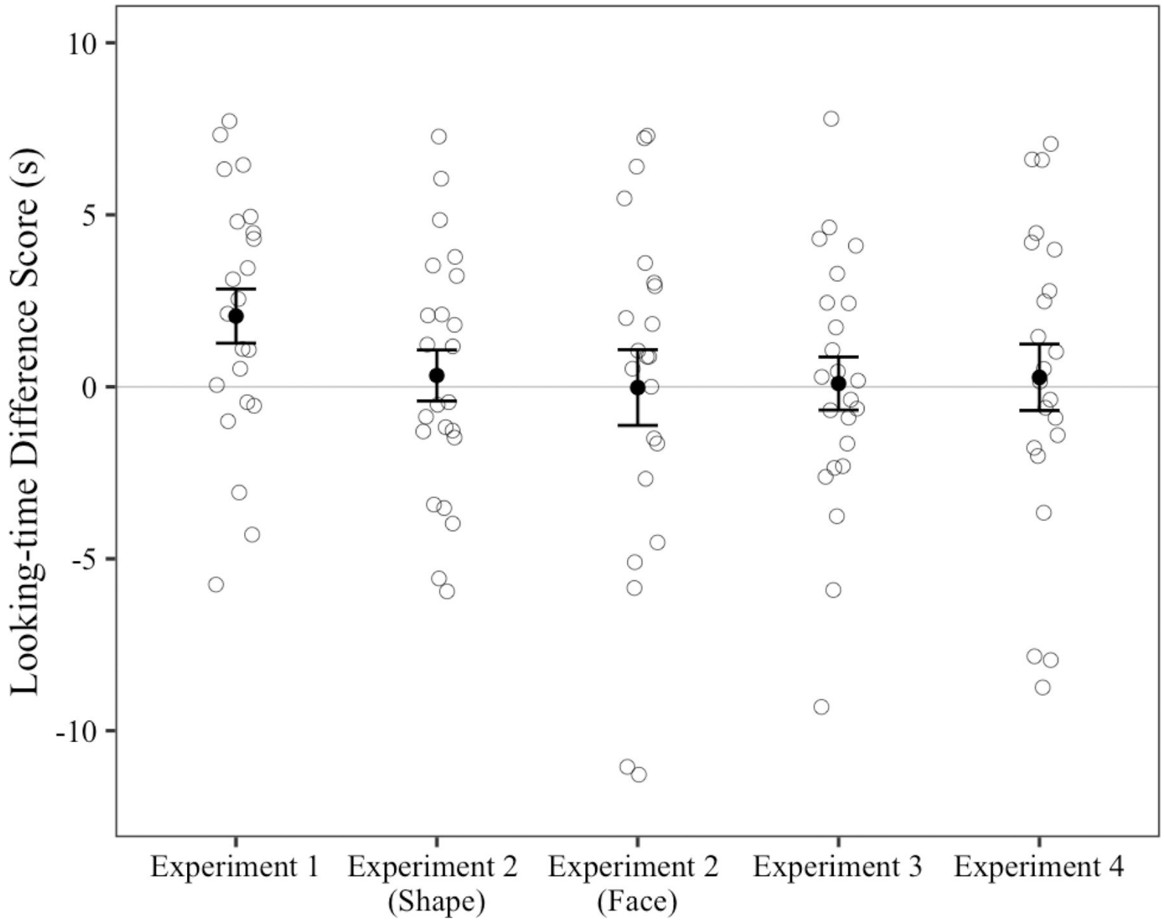

Figure 2.

Looking-time difference scores (average looking time on violation trials – looking time on consistent trials) for each infant by experiment. Filled points indicated the mean within each experiment, with error bars representing SEM. Note that scores above zero indicate novelty preferences, whereas scores below zero indicate familiarity preferences.

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Table 1.

Average time (in seconds) and number of trials to habituation by experiment

Experiment	Habituation Time (*SD*)	Habituation Trials (*SD*)
1	203 (73)	15.8 (5.0)
2 (Face)	238 (106)	16.0 (4.9)
2 (Shape)	235 (104)	15.8 (5.1)
3	192 (90)	14.9 (5.1)
4	195 (106)	14.5 (6.0)

Note. There were no significant differences in habituation time or trials across experiments, all *p*s > .10.

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Table 2.

Average looking times (in seconds) by experiment

Experiment	Consistent Trial Looking (*SD*)	Violation Trial Looking (*SD*)
1	8.23 (3.19)	10.28 (4.22)
2 (Face)	11.37 (5.28)	11.34 (5.27)
2 (Shape)	10.03 (4.03)	10.36 (3.53)
3	10.04 (4.41)	10.14 (4.03)
4	9.94 (3.91)	10.21 (4.10)