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Infants Learn About Objects From Statistics and People

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In laboratory experiments, infants are sensitive to patterns of visual features that co-occur (e.g., Fiser & Aslin, 2002). Once infants learn the statistical regularities, however, what do they do with that knowledge? Moreover, which patterns do infants learn in the cluttered world outside of the laboratory? Across 4 experiments, we show that 9-month-olds use this sensitivity to make inferences about object properties. In Experiment 1, 9-month-old infants expected co-occurring visual features to remain fused (i.e., infants looked longer when co-occurring features split apart than when they stayed together). Forming such expectations can help identify integral object parts for object individuation, recognition, and categorization. In Experiment 2, we increased the task difficulty by presenting the test stimuli simultaneously with a different spatial layout from the familiarization trials to provide a more ecologically valid condition. Infants did not make similar inferences in this more distracting test condition. However, Experiment 3 showed that a social cue did allow inferences in this more difficult test condition, and Experiment 4 showed that social cues helped infants choose patterns among distractor patterns during learning as well as during test. These findings suggest that infants can use feature co-occurrence to learn about objects and that social cues shape such foundational learning in distraction-filled environments.

Keywords: statistical learning, infancy, eye tracking, object perception, gaze following

To learn about the world, an infant must sift the lumps of useful information from a swirl of perceptual features. A growing literature shows that, in part, infants use the co-occurrence and reoccurrence of auditory and visual features to do this (Fiser & Aslin, 2002; Kirkham, Slemmer, & Johnson, 2002; Kirkham, Slemmer, Richardson, & Johnson, 2007; Saffran, Aslin, & Newport, 1996). For example, 9-month-old infants prefer to look at shapes that predictably co-occurred previously, rather than at shapes that did not co-occur in a predictable manner (Fiser & Aslin, 2002). Infants can then use statistical regularities inherent in the environment to identify what to learn and to make further inferences. Several developmental skills, such as object recognition (e.g., Biederman, 1987), categorization (Mareschal, Quinn, & French, 2002; Rakison & Butterworth, 1998; Schyns & Rodet, 1997; Younger & Cohen, 1986), and word learning (e.g., Estes, Evans, Alibali, & Saffran, 2007), benefit from learning the statistical regularities of visual and auditory features. During word learning, infants group co-occurring phonemes into words (Saffran et al., 1996) and then attach those newly segmented words to objects (Estes et al., 2007). In the literature on causal inference (e.g., Gopnik et al., 2004; Sobel & Kirkham, 2006), infants and toddlers used statistical regularities between events to make new predictions about which events would occur. Can infants similarly use the co-occurrence of features within an object to make new predictions about how the object will behave?

Binding co-occurring features is an essential skill for developing veridical representations of the visual world. Previous research has shown that adults chunk co-occurring features into larger perceptual units (e.g., Conway, Goldstone, & Christiansen, 2007; Fiser & Aslin, 2005; Goldstone, 2000; Orbán, Fiser, Aslin, & Lengyel, 2008). These larger units help identify discrete objects (Baker, Olson, & Behrmann, 2004; Turk-Browne, Isola, Scholl, & Treat, 2008; for a review, see Scholl, 2001). Co-occurrences can highlight the integral features of an object, which is the basis of visual categorization (Palmeri & Gauthier, 2004). Though no published studies have shown whether infants form expectations about object behavior on the basis of visual feature co-occurrence, some work has indicated that infants might be capable of doing this: Infants form expectations about how visual features should be grouped on

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the basis of other information, such as common motion (S. P. Johnson & Aslin, 1995; Kellman & Spelke, 1983), feature similarity (e.g., Quinn, Bhatt, Brush, Grimes, & Sharpnack, 2002), and physical constraints (e.g., nonfloating objects; Needham & Baillargeon, 1997), suggesting that infants might use statistical information in a similar way. Of importance, infants in the first year expect parts of objects to be cohesive (e.g., Cheries, Mitroff, Wynn, & Scholl, 2008; Spelke & Van de Walle, 1993).

However, even if infants can learn from co-occurrences, the natural environment often presents infants with multiple co-occurrences. How do infants know which co-occurrences to attend to, learn from, and maintain for use in further tasks? Social cues may help infants select appropriate information. By the first few months of life, infants engage in joint attention (Butterworth, 2004) elicited by eye gaze, infant-directed speech, initial eye contact, head turn, and gestures (Carpenter, Nagell, & Tomasello, 1998; Senju & Csibra, 2008). Many investigators have suggested that this attentional bias helps infants develop their social cognition and competence (e.g., understanding beliefs, desires, goals, and communicative intent; see Carpenter et al., 1998; Csibra & Gergely, 2006; Repacholi & Gopnik, 1997). However, these cues also can shape cognitive development by helping infants learn what to learn in a distraction-filled environment.

Although the impact of engaging in joint attention on social competence has been studied extensively (see Carpenter et al., 1998), fewer studies have investigated how following social cues can shape learning. Some studies have focused on word mapping (e.g., Gliga & Csibra, 2009; Houston-Price, Plunkett, & Duffy, 2006; Pruden, Hirsh-Pasek, Golinkoff, & Hennon, 2006; Yu, Smith, & Pereira, 2008) and learning linguistic structures (Goldstein & Schwade, 2008; Thiessen, Hill, & Saffran, 2005). For example, 15-month-olds are able to follow a turning face to an object and then map a spoken word onto that object rather than onto a noncued object (Houston-Price et al., 2006), and 7-month-olds can learn statistically defined auditory sequences better when they have been presented with infant-directed speech (as opposed to adult-directed speech; Thiessen et al., 2005). Other studies have shown that attending to the directed gaze of an adult can lead to better recognition of an attended object (e.g., 7-month-olds displayed a novelty preference for the noncued object; Cleveland, Schug, & Striano, 2007) as well as to encoding an object's featural or spatial information (9-month-olds looked longer at object feature changes when exposed to pointing gestures and looked longer at changes in object location when exposed to grasping gestures; Yoon, Johnson, & Csibra, 2008). Recently, Wu and Kirkham (2010) showed that social cues (i.e., a turning face that used infant-directed speech) produce better spatial learning of audiovisual events than nonsocial cues (i.e., flashing squares that shift attention to the target location) by 8 months of age. These findings suggest that following social cues could shape early statistical learning of object features. These conclusions, however, require more explicit measures of learning than recognition of cued objects or simple matching of audiovisual events.

In the current four experiments, we investigated how infants use both statistics and the people around them to learn about objects. We tested whether infants develop expectations about object integrity on the basis of feature co-occurrence and investigated the usefulness of social cues in helping infants select information to be learned and maintained. We were particularly interested in how social cues support learning and their use in noisy and distracting environments.

Experiment 1 (No Cue 1) investigated whether infants can form expectations about objects without any attention cues in a simple distraction-free paradigm. Infants were presented with a series of shape clusters, consisting of three shapes; two of the shapes always co-occurred, whereas the third shape changed in each presentation (Figure 1). After familiarization, infants saw sequentially presented test events that were either consistent or inconsistent with the previous co-occurrence information. In the consistent trials, the three-shape clusters split apart, with the previously co-occurring shapes remaining joined together and the third shape moving away. In the inconsistent trials, the three-shape clusters split apart with the previously co-occurring shapes moving away from each other (see Figure 1). If the infants processed the stimuli and were sensitive to the internal cluster statistics, longer looking to the inconsistent test events would be hypothesized, akin to a violation-of-expectation result.

Experiments 2, 3, and 4 investigated the effect of distraction during learning and test and the role of social cues in supporting selection, learning, and maintenance in these more difficult environments (Figure 2). In Experiment 2 (No Cue 2), the consistent and inconsistent test trials were presented simultaneously (rather than sequentially as in No Cue 1) to increase the task difficulty, because the simultaneous test presentation changed the spatial layout between familiarization (sequential presentation) and test trials (simultaneous presentation). This type of change has been suggested as one way to increase the difficulty level of an experimental task (e.g., Hunter & Ames, 1988; Quinn & Intraub, 2007). In addition, the simultaneous presentation of test events more closely resembled the noisy visual environment by adding an element of attentional choice to the paradigm. In Experiment 3 (Social Cue 1), we tested whether the presence of a social cue during familiarization would help focus attention and consequently boost infants' ability to discriminate between the test events in the same noisy and challenging test environment. In Experiment 4 (Social Cue 2), simultaneous presentation occurred during both the familiarization and test phases. During familiarization, two different sequences were presented simultaneously during familiarization (again to better mimic the natural environment by presenting distraction), and the social cue directed infants' attention to one of the two familiarization sequences. In all experiments, we used eye-tracking technology to measure overt visual attention during familiarization and test trials.

Experiment 1

Our initial exploration of the role of feature co-occurrence on the expectations of object behavior presented infants with a simple spatial layout (Figure 2, left panel), maintaining the same spatial layout (sequential presentation) between familiarization and test trials (No Cue 1).

Method

Participants. Eighteen 9-month-olds (nine female, nine male; age: M = 9 months, 1 day; range = 8 months, 14 days to 9 months 23 days) participated in this experiment. Three infants were excluded from final analyses because of fussiness (i.e., com-

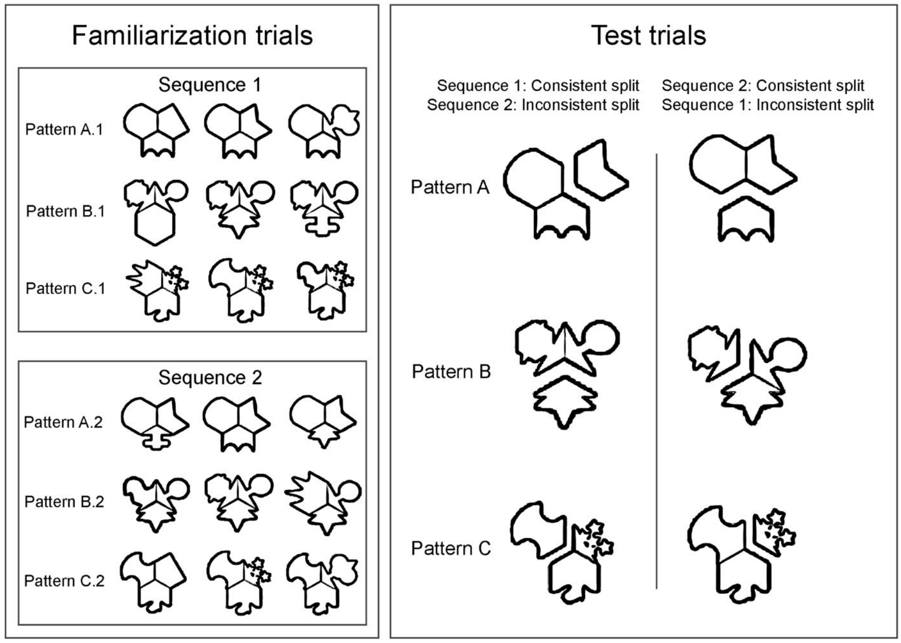

Figure 1. Shape cluster stimuli and patterns during familiarization and test trials. All stimuli loomed in full color on a black background.

pleting only two out of four blocks). Thirteen infants completed all four blocks; the remaining five infants completed three blocks. Infants were recruited through local-area advertisements and given T-shirts for participating.

Apparatus. Infants' gaze was recorded with a Tobii 1750 eye-tracker (www.tobii.com), and events were presented on a 17-in. monitor attached to the eye-tracking unit. Stimuli were displayed with Tobii's ClearView AVI presentation software, and sounds were played through stereo external speakers. The shape animations were created with Macromedia Director MX 2004, and the movie clips were assembled with Final Cut Express HD 3 (Apple Inc., CA).

Stimuli. During the familiarization trials, infants watched sequences of looming three-shape clusters, which appeared in one of two white frames in the bottom corners of the screen (side was counterbalanced across participants). Each sequence contained three patterns of shape clusters (Patterns A, B, and C), and each pattern was composed of two co-occurring shapes and one constantly changing shape. The shapes differed from each other in color and shape. Each infant saw one sequence (repeatedly) during familiarization (Sequence 1 or Sequence 2) with a total of nine shape clusters in each sequence (three clusters per pattern, three patterns per sequence). Each cluster loomed from a minimum of 4.87° to a maximum of 9.72° for 2 s. When a cluster grew to its maximum size, it disappeared from the screen, and another cluster appeared. A single sequence appeared in one of two white frames arranged left and right in the lower half of a black screen. Infants viewed the looming pattern while the other frame remained empty (see Figure 3).

During the test trials, infants were shown consistent and inconsistent splitting events. Consistent events showed an animation of a three-shape cluster breaking into two parts, with the shape that had been constantly changing during familiarization moving apart from the other previously co-occurring, paired shapes. Inconsistent events showed shapes that had been paired together splitting apart, where one stayed with the shape that had been changing during familiarization. The same test events were seen by all infants. The events were labeled as *consistent* or *inconsistent* according to the pattern that each infant saw during familiarization (i.e., a test event that was a consistent split for Sequence 1 was inconsistent for Sequence 2, and vice versa). Thus, differences in looking time for test events were due to the exposure during familiarization rather than basic perceptual preferences. Each splitting event loomed from a minimum of 4.87° to a maximum of 8.51° for 2 s. Then, either a variable or constant shape split off at a 45°, 180°, or 270° angle (relative to the vertical depending on its position in the cluster) for another 2 s until it reached 9.72°. These test events appeared in the same lower left or right frame as the familiarization events. Consistent and inconsistent test events were shown sequentially in the frame (see Figure 3).

Design and procedure. Infants sat in a car seat 50 cm from the eye-tracker monitor in a small, quiet room, while their caregivers sat out of their view. The caregivers were instructed to refrain from commenting on the movies or interacting with their infant. The experimenter used a 5-point calibration with a Sesame Street clip on the infants' looks. For the experiment, infants were shown four blocks of trials, consisting of familiarization trials followed by test trials. Each block consisted of the following: (a) six familiarization trials (i.e., two per pattern, with each pattern consisting of three looming shape clusters; see Figure 1), each of which lasted 6 s, and (b) two test trials (one consistent and one inconsistent, with order counterbalanced across infants) that lasted 12 s per trial (three splitting events per trial, one from each pattern; see Figure 3). During each familiarization trial, the three different

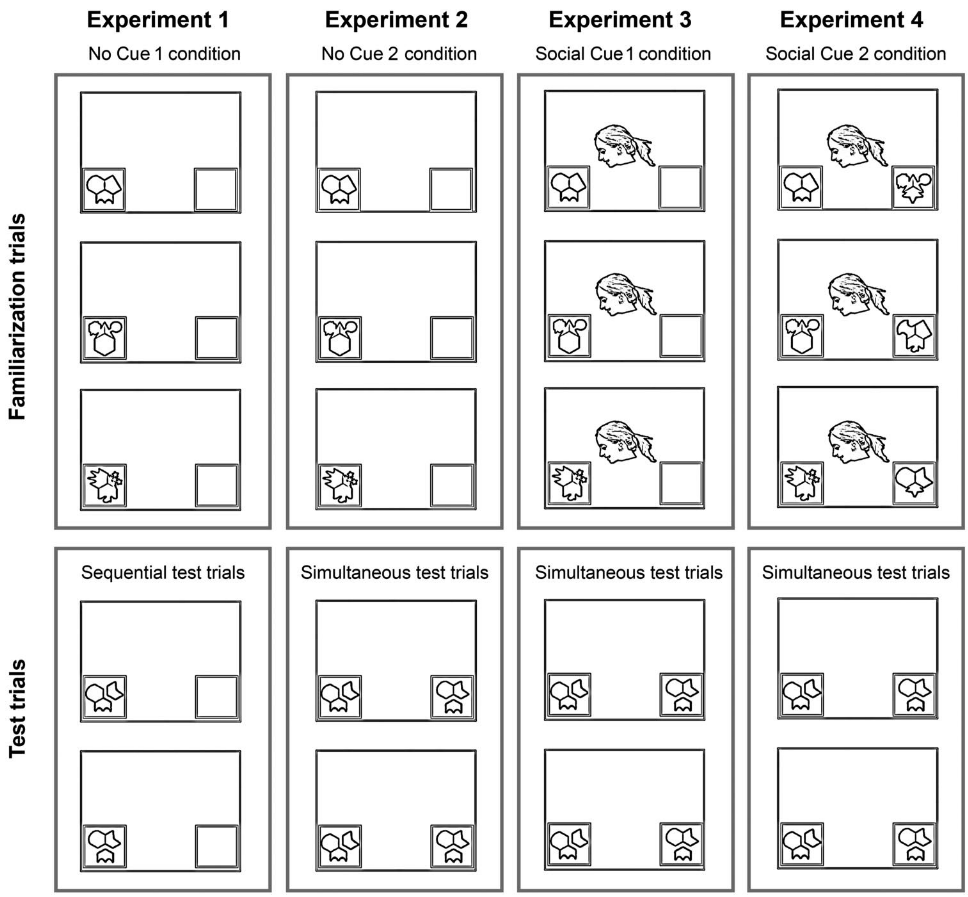

Figure 2. Familiarization and test trials for the four conditions in Experiments 1 through 4. All stimuli were in full color on a black background.

shape clusters in a given pattern were presented sequentially. The training sequence (Sequence 1 or 2) and presentation side were counterbalanced across infants. For each infant, the clusters in the test trials were presented in four orders, which were counterbalanced with a Latin square across all infants. Whether the first test trial displayed an inconsistent or consistent pattern also was counterbalanced across infants. Blocks 3 and 4 repeated all familiarization and test trials from Blocks 1 and 2. Attention getters (static kaleidoscopic circles or squares with either a *bring* or a *boing* sound) occurred between each familiarization and test trial. The 1-s clip looped until the infants returned their gaze to the screen for approximately 1,500 ms, as monitored by the experimenter though an external video camera and controlled with keypresses.

Coding. The areas of interest encompassed slightly larger areas than those of the frames to account for noisy infant saccades and small calibration errors. For the familiarization trials, total looking time for the area of interest containing the target event was calculated with Tobii's ClearView analysis software. For the test trials, a proportional looking time difference score was calculated by subtracting the percentage of time looking at the inconsistent events (total time looking at the inconsistent event divided by the total time looking at both test stimuli) from the percentage of time looking at the consistent event. A negative score reflected a preference for the inconsistent splits, and a positive score reflected a preference for the consistent splits.

Results

Infants looked at the familiarization sequence for an average of 67.15 s (SE = 4.28), 46.63% of the entire presentation time. Analyses revealed a significant decrement in looking time across blocks, $F(3, 36) = 18.70$, $p < .001$ (Bonferroni-corrected comparison between Blocks 1 and 4, $p = .001$), suggesting processing of the stimuli. A one-sample t test on the test trials revealed that there was a mean preference for the inconsistent splits overall and that this preference was significantly higher than chance, $t(17) = -2.33$, $p = .03$, two-tailed (Table 1). There was no difference between blocks, $F(3, 33) = 1.78$, $p = .17$, partial $\eta^2 = .14$.

Discussion

Across all four blocks, infants displayed an overall preference for the inconsistent split. This result suggests that the infants were sensitive to the statistics of the shapes within each cluster, showing a violation-of-expectation effect when the two previously co-occurring shapes split apart. This finding fits well with previous

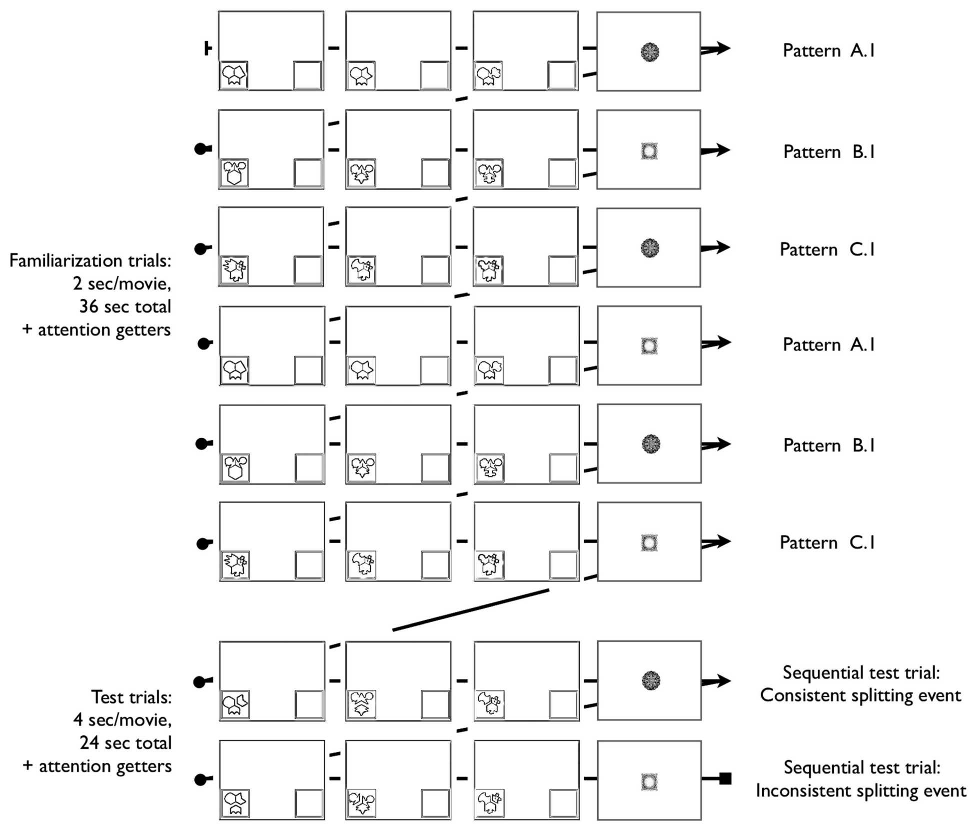

Figure 3. A schematic of one sample block (trial by trial) from the No Cue 1 condition. Each infant was presented with up to four blocks.

work suggesting that infants at this age are sensitive to co-occurrence in simultaneous shape displays (Fiser & Aslin, 2002). In Fiser and Aslin (2002), 9-month-olds showed a familiarity preference for previously co-occurring shapes. It is worth noting that studies that have presented many different stimuli during the habituation phase often lead infants to show familiarity preferences instead of novelty preferences, perhaps because of less than complete encoding of the many potential sources of information in the habituation stimuli (R. Aslin, personal communication, March 24, 2011). In addition, Fiser and Aslin asked infants to abstract some interpretation from the training trials by showing novel stimuli during test, which also may have driven the familiarity

Table 1
Looking Times During Familiarization and Test Trials Across Four Blocks in Four Conditions

	Condition							
	Experiment 1: No Cue 1		Experiment 2: No Cue 2		Experiment 3: Social Cue 1		Experiment 4: Social Cue 2	
Looking time	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
				Familiarization trials				
Total looking time (s)	67.15	4.28	68.39	5.30	43.84	5.53	39.14	4.49
Difference score (DS)							0.42	0.05
				Test trials				
Block 1 DS	−0.02	0.10	−0.04	0.09	−0.14	0.09	−0.08	0.07
Block 2 DS	−0.06	0.08	0.23	0.11	−0.13	0.07	−0.12	0.08
Block 3 DS	−0.10	0.11	0.18	0.12	−0.07	0.07	−0.04	0.06
Block 4 DS	−0.30	0.14	0.27	0.12	−0.09	0.10	−0.14	0.05
Mean DS	−0.11*	0.05	0.14	0.09	−0.11*	0.05	−0.09*	0.04

* $p \leq .05$, two tailed.

preference instead of a novelty preference. In this paradigm, we presented infants with fewer shape clusters during training (compared with Fiser & Aslin, 2002), and then we presented the same clusters again during test, which may explain why we found a violation-of-expectation or a novelty preference.

The results from this experiment suggest that in a simple distraction-free environment, 9-month-olds are capable of learning about the statistics of a three-part unit and may be capable of forming expectations about this unit. In the natural environment, however, there are distractions and irrelevant information that must be filtered for infants to make, maintain, and use such inferences effectively.

Experiment 2

Experiment 2 was designed to address whether distraction during test would indeed make the task more difficult, suggesting that infants might be unable to maintain the inferences they made during the familiarization trials in a more distracting test environment. Infants were shown the familiarization sequence by itself, with no attention cue and no distraction (No Cue 2). However, although the familiarization events remained the same as in the No Cue 1 condition, the splitting events at test were presented simultaneously (rather than sequentially) in the lower left and right frames, with the location of inconsistent and consistent events counterbalanced across infants. In other words, half the infants saw the consistent splits in the same spatial location as the previous familiarization trials (congruent), and half the infants saw the inconsistent splits in that location (incongruent).

Method

Participants. Eighteen 9-month-olds (nine female, nine male; age: $M = 9$ months, 6 days; range = 8 months, 18 days to 9 months, 26 days) participated in the No Cue 2 condition. Two infants completed three blocks in this condition, and the rest completed all four blocks. Three infants were excluded from final analyses because of fussiness (i.e., completing two blocks).

Stimuli, design, and procedure. Experiment 2 used the same shape stimuli from Experiment 1; the familiarization trials in the No Cue 2 condition were identical to those from Experiment 1 (No Cue 1). With the exception of the simultaneous presentation of the test trials, all aspects of the procedure were the same as in Experiment 1. In this experiment, we implemented a preferential looking paradigm during test trials by presenting the consistent and inconsistent splits simultaneously in both the right and left locations to increase the complexity of the display. Locations of the splitting events were counterbalanced across infants. To maintain consistency for presentation time and trial numbers, there were two test trials per block that showed the inconsistent and consistent splits simultaneously.

Coding. Because the test trials now included simultaneous consistent and inconsistent splits, the difference score was calculated by subtracting the inconsistent proportional looking time from the consistent proportional looking time for each trial.

Results

Infants in the No Cue 2 condition looked at the familiarization sequence an average of 68.39 s ($SE = 5.30$), 47.49% of the entire presentation time; these times are similar to those in Experiment 1, $t(34) = 0.18$, $p = .86$. Analyses revealed a significant decrement in looking time across blocks, $F(3, 45) = 7.43$, $p < .001$ (Bonferroni-corrected comparison between Blocks 1 and 4, $p = .01$). There was no significant preference overall during test, $M = 0.14$, $SE = 0.09$, $t(17) = 1.53$, $p = .15$ (Figure 4).

We used a one-way analysis of variance (ANOVA) to investigate whether congruency between familiarization and test presentation side affected test preference (whether infants looked longer at inconsistent patterns in novel locations). We found no significant effects of congruence on the average difference score for the No Cue 2 condition, $F(1, 16) = 0.78$, $p = .39$.

There was a main effect of block, $F(3, 42) = 4.48$, $p = .008$, partial $\eta^2 = .24$. Bonferroni-corrected post hoc comparisons revealed a significant difference in looking times between Blocks 1 and 2 ($p = .02$) and a marginal difference between Blocks 1 and 3 ($p = .08$) but no difference between Blocks 1 and 4 ($p = .19$).

Discussion

With the addition of a noisier test layout, infants showed no significant preference for either the consistent or inconsistent splitting event during test, whether the test layout was congruent or incongruent with the familiarization layout. This outcome differed from that of Experiment 1, in which infants showed a preference for the inconsistent splitting event. Looking more closely at the proportional looking time during test, one can see that infants displayed a nonsignificant preference for the consistent event, a preference that developed across four blocks and was as large as that in Experiment 1 (No Cue 1), albeit noisier. Although this is a nonsignificant effect, the flip in preference between the two conditions could support our conclusion that task difficulty was increased. In habituation paradigms, there is well-documented evidence that familiarity preferences are more likely to occur when the task is more difficult (see Houston-Price & Nakai, 2004; Hunter & Ames, 1988; Roder, Bushnell, & Sasseville, 2000). We suggest that similar to changes in familiarity and novelty preferences in habituation paradigms, increasing task difficulty could drive a preference for the consistent event, which may precede that

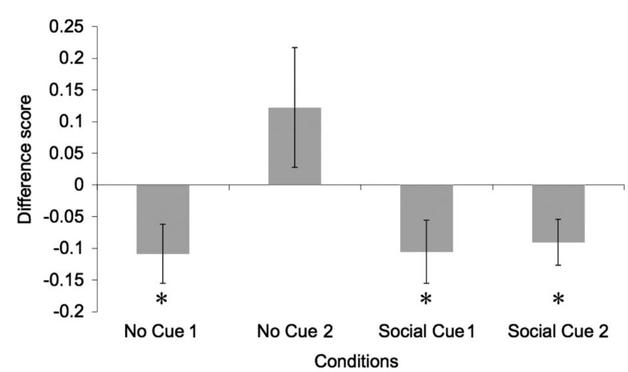

Figure 4. Difference scores across conditions (mean difference between proportional looking times for consistent minus inconsistent events during test). A negative value reflected a preference for the inconsistent splits (i.e., looking longer at events showing the separation of features that co-occurred rather than the separation of features that did not co-occur). Error bars represent standard errors. * $p \leq .05$, two tailed.

for the inconsistent event. Though this preference flip is well documented for habituation paradigms, it does not seem to be well documented for violation-of-expectation paradigms (Kuhlmeier, Wynn, & Bloom, 2003; M. Moher, personal communication, May 17, 2010).

In summary, one conclusion that can be drawn from this result is that the noisier test layout increased task difficulty during test. Another possibility is that the stimuli during familiarization were not processed deeply enough for infants to show learning in this new, more distracting test layout. In other words, perhaps stimuli were processed deeply enough to show learning in a simple test layout (Experiment 1) but not when attentional choice was required during test (Experiment 2). This second possibility is probably not the case, given that there was no significant difference between looking times at the target during familiarization in Experiment 1 and Experiment 2. In addition, infants displayed a decrement in looking time for the familiarization stimuli, suggesting processing of the stimuli.

Experiment 3

Given the lack of a significant preference in Experiment 2, we examined the effect of introducing a social cue during familiarization. To explore how social cues might support processing and, in turn, influence infants' expectations of feature co-occurrences in complex situations (Figure 2, third panel), infants were shown the familiarization sequence with a face cue that turned toward the familiarization patterns (Social Cue 1).

Method

Participants. Seventeen 9-month-olds (seven female, 10 male; age: $M = 9$ months, 6 days, range = 8 months, 14 days to 9 months, 20 days) participated in the Social Cue 1 condition. Two infants were excluded from final analyses because of fussiness (i.e., completing two blocks) and equipment failure. All infants completed all four blocks.

Stimuli, design, and procedure. The familiarization patterns in Social Cue 1 were identical to those from Experiments 1 and 2. For this condition, prior to the onset of the shape pattern, a video of a female face appeared in the center of the screen, looked forward, smiled, said "Hi baby, look at this!", and turned to look down at a frame. Immediately after the face stopped turning, the familiarization pattern appeared in that frame. The face stayed turned and smiling until the pattern finished (after displaying three clusters sequentially). The pattern disappeared, and the face turned back to the center and changed to a neutral expression as the trial ended. At the beginning of each familiarization trial, the face clip lasted for 5 s before the onset of the pattern. Test trials were the same as in Experiment 2, with simultaneous presentations of inconsistent and consistent splitting events (respective locations counterbalanced across infants).

Coding. A central area of interest was added to the familiarization trials because of the addition of the central face cue. The rest of the coding was identical to the coding in Experiment 2.

Results

Infants in the Social Cue 1 condition looked at the familiarization pattern for an average of 43.84 s ($SE = 5.53$), 30.44% of the entire presentation time; this was a shorter duration compared with times for infants in the No Cue 1 condition, $t(33) = 3.27$, $p = .003$, and the No Cue 2 condition, $t(33) = 3.12$, $p = .004$. Analyses revealed a significant decrement in looking time across blocks, $F(3, 48) = 17.64$, $p < .001$ (Bonferroni-corrected comparison between Blocks 1 and 4, $p < .001$). Infants in the Social Cue 1 condition displayed a preference for the inconsistent split during test, $t(16) = -2.12$, $p = .05$ (Figure 4).

A one-way ANOVA investigating whether congruency between familiarization and test presentation side affected test preference (whether infants looked at inconsistent patterns in novel locations for a longer time) revealed no significant effects of switching on the average difference score, $F(1, 15) < .01$, $p > .90$. There was no difference between blocks, $F(3, 48) = 0.16$, $p = .92$, partial $\eta^2 = .01$.

Discussion

Across all four blocks, infants in this condition exhibited a preference for the inconsistent split during test, despite looking at the patterns for less time during familiarization than did infants in the No Cue 1 and No Cue 2 conditions. In other words, even though infants spent less time looking at the patterns during familiarization, they appeared to process and maintain the information deeply enough to show a preference for the inconsistent splitting event during test (a preference similar to the one in No Cue 1, without distractions). Of importance, this preference occurred with simultaneous test events, which were identical to those in Experiment 2 but more distracting than those in Experiment 1. In Experiment 2, with no social cue, infants seemed to be unable to use the familiarization information at test, but when the social cue was added, infants were much better at retaining and using the information. It is possible that the preference for the inconsistent event was based on less processing during familiarization (given infants' shorter looking times during familiarization). However, a steady decrement in looking time during familiarization to the target stimuli suggests processing of that stimuli. The fact that there was no difference between the congruent and incongruent conditions suggests, in addition, that social cues may help infants overcome difficulties associated with changing spatial layouts between familiarization and test during an experiment.

Experiment 4

In the last experiment, we presented infants with a noisy and distracting learning environment (during familiarization) in addition to the distracting test environment (Social Cue 2; Figure 2, fourth panel). This setup is a little closer to the situation an infant encounters in the real world, where there are many potential sources of statistical structure that could be learned. Moreover, as is also often the case for the infant, there is a social cue present that could direct and shape learning.

In addition, in this experiment, unlike the previous experiment, the social cue actually directed the infant to one set of information that would lead to one conclusion rather than to another set of information that would lead to a different conclusion. It is possible that the positive effect of the social cue in Experiment 3 versus Experiment 2 was simply due to generally enhanced attention to the display—and that the mere presence of the face was sufficient to explain the results. In the current experiment, however, the social cue actually directed infants to one part of the display rather than another. Moreover, in the current experiment, the face was always present and was always in the same central location in the screen. All that differed across trials was whether the face looked toward one set of events rather than the other simultaneous events during familiarization.

Method

Participants. Eighteen 9-month-olds (10 female, eight male; age: $M = 9$ months, 3 days, range = 8 months, 24 days to 9 months, 22 days) participated in this experiment. Five infants completed three blocks, and 13 infants completed all four blocks.

Stimuli, design, and procedure. During the familiarization phase, two sequences were presented simultaneously in the two white frames in the bottom corners of the screen. The familiarization patterns were the same as in Experiments 1, 2, and 3, but in this experiment, both sequences (1 and 2) were presented to each infant; the social cue directed the infant's attention to one of the sequences. Whereas in the previous experiments infants saw either Sequence 1 or Sequence 2 during familiarization, in this experiment, infants were presented with both sequences but were consistently cued to only one of them (see Figure 2). Infants who were directed to look at Sequence 1 had Sequence 2 as the distractor event, and vice versa. Therefore, the sequence that was the target for one infant was the distractor for another. Test events were presented simultaneously and were identical to those in Experiments 2 and 3.

Results

To measure the efficacy of social cues during familiarization, a difference score for the familiarization trials was calculated in the same manner as for the test trials, except for the inclusion of the central area of interest (face). Infants looked at the cued familiarization pattern for 27.18% of the entire presentation time ($M = 39.14$ s, $SE = 4.49$) and looked at the noncued pattern for 10% of the time ($M = 14.40$ s, $SE = 1.65$). The total looking time for the target (cued) patterns was similar to that from the Social Cue 1 condition (Bonferroni-corrected comparison, $p = 1.00$) and was significantly shorter than the looking times for the No Cue 1 and No Cue 2 conditions ($p < .001$). Difference scores during familiarization indicated that 17 infants (94.44%) looked longer at the cued pattern than at the noncued pattern, $t(17) = 7.67$, $p < .01$. Analyses revealed a significant decrement in looking times for the cued patterns across blocks, $F(3, 36) = 12.71$, $p < .001$ (Bonferroni-corrected comparison between Blocks 1 and 4, $p = .01$), suggesting processing of the cued target stimuli. For the test trials, a t test on the difference score revealed a preference for the inconsistent splitting events compared with chance, $t(17) = -2.48$, $p = .02$.

An ANOVA on the effect of congruency (location of cued familiarization sequence and location of test events) revealed no significant effects of congruency on the average difference score, $F(1, 16) = 0.55$, $p = .47$. There was no difference between blocks, $F(3, 36) = 0.85$, $p = .48$, partial $\eta^2 = .07$. A one-way ANOVA on all the experiments revealed a significant difference in average proportional looking time during test trials across all four experiments, $F(3, 67) = 4.07$, $p = .01$. Bonferroni-corrected comparisons revealed that the looking times during test from the No Cue 2 condition (Experiment 2) were significantly different from those from the No Cue 1 condition (Experiment 1), $p = .05$; those from the Social Cue 1 condition (Experiment 3), $p = .03$; and those from the Social Cue 2 condition (Experiment 4), $p = .03$. The other three experiments did not differ from each other, $p = 1.00$.

Discussion

Across all four blocks, infants displayed a preference for the inconsistent split, similar to the preference in Experiment 1 (No Cue 1) and Experiment 3 (Social Cue 1). Infants showed this preference despite being exposed to another pattern in the other frame during familiarization. The finding from this fourth experiment suggests that the social cue focused infants' attention on the cued target pattern and supported the processing of it to form a representation of the event. Infants' preference for the split that was inconsistent with the target familiarization pattern suggests that they did not process much of the distractor pattern. Between-experiment analyses confirmed that the overall test preferences in Experiments 1, 3, and 4 differed from that in Experiment 2.

General Discussion

We have shown that 9-month-olds use visual feature co-occurrences to form representations of object integrity and that with multiple streams of visual information available in their environment, infants use social cues to select the ones that they learn. These findings show that infants go beyond the simple detection of statistical regularities among events (e.g., Fiser & Aslin, 2002) to use that information to make new predictions about object behavior. Through tracking feature co-occurrences, infants can identify larger perceptual units, which can inform them about integral units of objects. Tracking units in this manner supports object individuation, recognition, and categorization. The fact that statistics are useful for infants in the visual domain echoes findings in the auditory domain (Estes et al., 2007) and in studies of causal inference (Sobel & Kirkham, 2006). Our findings support the idea that statistical learning is a powerful mechanism that is useful in the visual domain and that leads to inferences beyond detection of the statistical pattern itself.

Social attention cues can shape infants' learning about objects and improve the maintenance of that learning, the second finding in our experiments. These effects remained despite the distraction of the face itself, change in spatial layout from familiarization to test trials, and additional distractor patterns during familiarization. By using a complex measure of learning, this study provides strong evidence that social cues can shape learning from the first year, contributing to an emerging literature on this topic (e.g., Goldstein & Schwade, 2008; Yoon et al., 2008).

One could ask whether the social character of the face drove the learning effect in complex situations or whether a nonsocial cue would have been equally effective. In this regard, it is noteworthy that the face appeared equidistant from the target and distractor frame during familiarization. Hence, it was not merely the presence of the face that facilitated learning but that the face directed attention toward one stimulus rather than another. A comparative nonsocial cue that is as effective as the social cue should have this same directive quality.

An attention-directing nonsocial central cue in infancy is an interactive stimulus: If a stimulus interacts with the infant and then turns in one clear direction, the infant will follow the object's "gaze" (e.g., S. C. Johnson, Slaughter, & Carey, 1998). A recent study, however, showed that 18-month-olds do not map labels onto objects "gazed" on by an interactive nonsocial stimulus (i.e., a robot), only on those gazed on by human faces (O'Connell, Poulin-Dubois, Demke, & Guay, 2009). Perhaps 9-month-old infants may learn from such a stimulus unlike their older peers, though the interactive stimulus might be argued to itself have social features. In future studies, we intend to find a suitable nonsocial cue for this experimental paradigm. For now, we claim only that social cues facilitate visual statistical learning, both in choosing specific patterns among other noncued patterns and in maintaining learned preferences despite changes in spatial layout. We do not claim, however, that social cues are the only attention cues that aid learning.

We found that co-occurrence information and social cues inform and direct learning during infancy (though from this series of experiments, we cannot draw conclusions about similarities in mechanisms driving learning with and without social cues). Though social cues may temporarily detract attention away from certain learning events in the world, they appear to stimulate infants to better maintain and use what they have learned in complex situations than when infants learn on their own without attention cues in the same situations. Investigating how infants interact with different cues in the environment (see Goldstein et al., in press) and the developmental trajectory of the use of such cues (e.g., Hollich, Hirsh-Pasek, & Golinkoff, 2000) would clarify the extent to which these cues shape cognitive development and would allow researchers to understand how infants learn to learn.

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