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Brief Report

The importance of "what": Infants use featural information to index events

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ABSTRACT

Dynamic spatial indexing is the ability to encode, remember, and track the location of complex events. For example, in a previous study, 6-month-old infants were familiarized to a toy making a particular sound in a particular location, and later they fixated that empty location when they heard the sound presented alone (*Journal of Experimental Psychology: General*, 2004, Vol. 133, pp. 46–62). The basis and developmental trajectory of this ability are currently unclear. We investigated dynamic spatial indexing across the first year after birth and tested the hypothesis that the structure of visual cues supports infants' learning of sound and location associations. In our study, 3-, 6-, and 10-month-olds were tested in a dynamic spatial indexing eye movement paradigm that paired two sounds with two locations. In one condition, these were reliably paired with two sets of visual features (*two toys* condition), replicating the original studies. We also presented a single set of visual cues in both locations (*one toy* condition) and multiple sets of visual features in both locations (*six toys* condition). Infants from 3 months of age onward showed evidence of dynamic spatial indexing in the two toys condition, but only the 10-month-olds succeeded in the one toy and six toys conditions. We argue that this may reflect a broader developmental trajectory, whereby infants first make use of multiple cue integration but with age are able to learn from a narrow set of cues.

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Introduction

In this study, we investigated the developmental trajectory of the ability to encode, track, and retrieve complex multimodal events, which we term *dynamic spatial indexing* (DSI). This requires the coordination of perceptual and cognitive skills: rapid automatic encoding of spatial information (Nissen, 1985), tracking the locations of multiple dynamic objects (Pylyshyn & Storm, 1988), and the organization of spatial locations and audiovisual events that can be used to ''look up'' information about objects (Ballard, Hayhoe, Pook, & Rao, 1997). This particular cluster of faculties is crucial in navigating and learning about a multimodal changing environment (see Richardson & Spivey, 2000; see also Richardson & Kirkham, 2004, for a review of how this ability relates to the development of working memory, spatial attention, and cross-modal perception).

DSI was first observed in adults (Richardson & Spivey, 2000). Participants were presented with spoken information while looking at a speaker in a grid. Later, when recalling that information, participants looked at the now-empty location where the speaker had previously appeared. This suggests that object-based attention (Hoover & Richardson, 2008) serves to bind information to locations on the screen.

Surprisingly, very similar abilities were seen in 6-month-old infants. Richardson and Kirkham (2004) showed infants two toys on a computer screen. Each toy moved in synchrony with a unique sound in one of two square frames at the top and bottom of the screen (Fig. 1). Following familiarization, the two now-empty frames moved from their vertical orientation to a horizontal one, and infants heard one of the sounds again. Infants looked more at the frame that had previously contained the associated toy even though it was now empty and in a different location on the screen.

Although they demonstrated the presence of DSI during infancy, these original studies were silent on a vital developmental question: What information were infants using to perform the task? At each presentation of an event inside one of frames, three cues were combined. A toy with unique visual features and unique auditory features appeared in a unique location. At test, only two of these cues were examined. The auditory cues were replayed, and the infant fixated an empty location. It is possible, therefore, that the particular visual cues of the toy play no role in DSI. All that is required is that *something* appears in a particular location during presentation, so that an association between a sound and a location can be learned. Here, we contrasted this *minimal cue* hypothesis with the *multiple cue integration* hypothesis, which holds that learning is supported by structure and covariation across cues (Kirkham, Slemmer, Richardson, & Johnson, 2007). In the case of the DSI paradigm, it suggests that infants' learning of sound and location associations will be boosted by regular covariation in the toys' visual features. We investigated these hypotheses across the first year after birth.

Infants were tested in a DSI paradigm that paired two sounds with two locations. In Experiment 1 (*two toys* condition), these were reliably paired with two sets of visual features, replicating the original studies. In Experiment 2 (*one toy* condition), a single set of visual features was seen in both locations. In Experiment 3 (*six toys* condition), multiple sets of visual features appeared in both locations in turn. Finally, in Experiment 4, we investigated infants' use of spatiotemporal cues by presenting them with two identical toys that were constantly on the screen during the presentation stage (*constant toys* condition). A developmental trajectory emerged in which infants' early reliance on multiple cues gives way to their ability to learn from a narrower set of cues.

Experiment 1

The first experiment had two goals: (a) to replicate the original dynamic spatial indexing finding with 6-month-olds and (b) to examine performance in a younger age group of 3-month-olds.

Method

Participants

In total, 9 full-term 3-month-olds (6 female and 3 male, mean age = 3.3 months, *SD* = 0.2) and 13 full-term 6-month-olds (7 female and 6 male, mean age = 6.2 months, *SD* = 0.3) comprised the final sample. An additional 10 6-month-olds and 5 3-month-olds were observed but not included in the

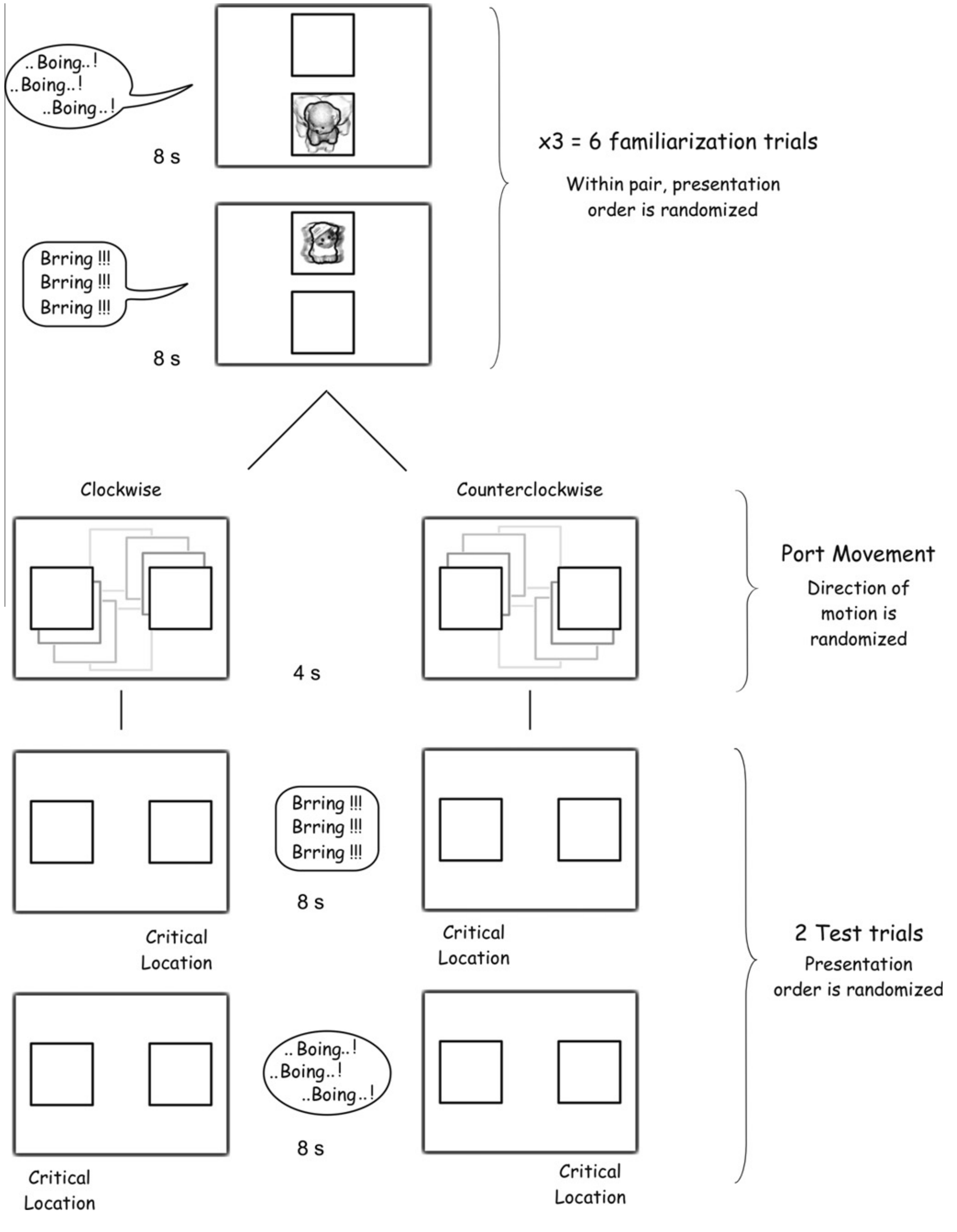

Fig. 1. Schematic of dynamic spatial indexing paradigm (two toy condition).

analyses because of fussiness or poor calibration. The infants were recruited by telephone from a database of parents who had previously indicated willingness to participate. Parents and infants received a small gift (a baby T-shirt or toy) for their participation.

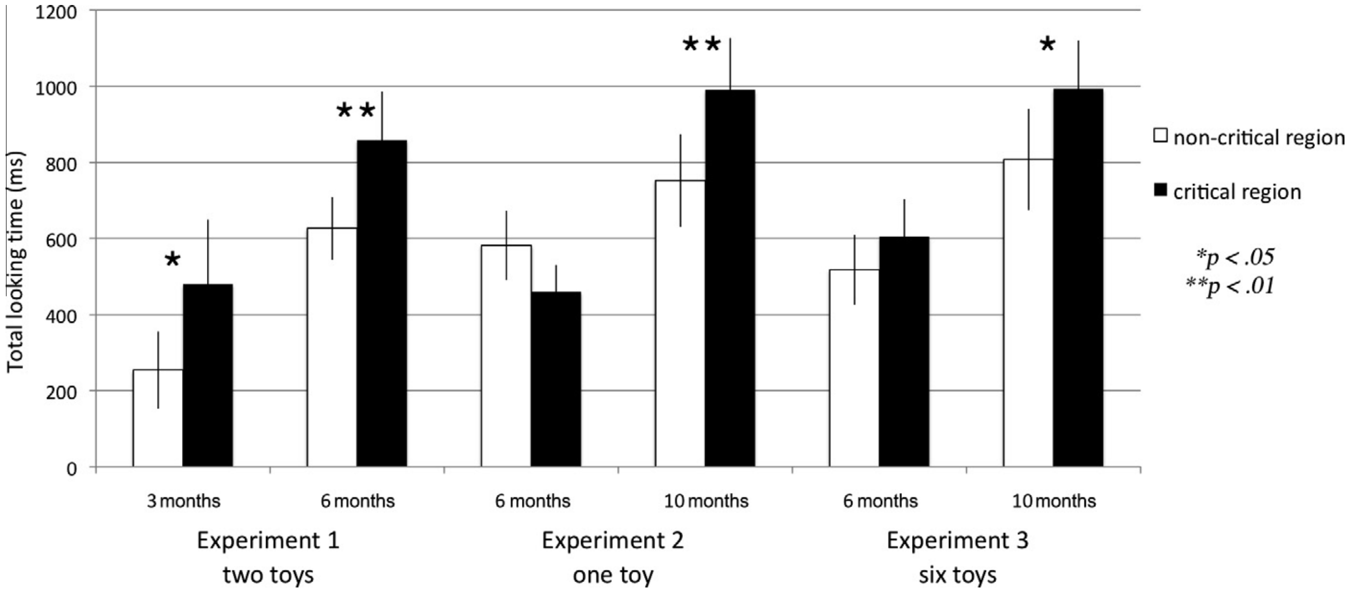

Fig. 2. Mean looking times of infants across all experiments. Bars show standard errors.

Apparatus

A Mac computer and 152-cm rear projection screen presented the stimuli. Each infant sat on the caregiver's lap 180 cm from the screen. An Applied Science Laboratories Model 504 corneal reflection eye tracking system (Bedford, MA, USA) placed below the display collected data at 30 Hz. A digital video recorder taped an audiovisual record of the stimulus display and the infant's point of gaze.

Procedure

Prior to the experiment, the infant was shown a cartoon as the experimenter directed the pupil camera toward the eye. The camera then automatically tracked the pupil despite small displacements of the infant's head; occasional large head movements required the experimenter to relocate the pupil. A two-point calibration routine was performed using an attention-getter that subtended a 5.2° visual angle at its fullest extent and was presented at the top left and bottom right of the screen. Blocks of trials (six familiarization trials and two test trials) were presented repeatedly until the infant lost interest.

Stimuli

On a black background, two white square frames were on the screen at all times (see Fig. 1), each subtending 11.4° and centered 10.3° from the midline. For each infant, pictures of two toys were randomly chosen from a set of six toys (rattle, cat, dog, pig, duck, and keys), each subtending approximately 8°, and were randomly allocated a sound from a set of four sounds (ringing noise, bouncing sound, whoosh, and musical rhythm). Short 6-s movies were made of the toys moving in time with the sounds. These movies were randomly paired to the two frames and appeared in only those locations for the duration of the experiment.

Design

Blocks began with six familiarization trials consisting of three presentations of one toy and three of the other. Order of presentation was randomized so that the infant never saw the same toy more than twice in succession. Each trial began with a centrally presented attention-getter remaining on the screen until the experimenter signaled that it had been fixated. A movie of a toy then appeared for 8 s in one frame. After six such trials, infants watched for 2 s as the two frames moved smoothly from a vertical alignment to a horizontal alignment. The direction of this rotation was chosen at random.

Each of the two test trials began with an attention-getter in the middle of the screen. When the experimenter indicated that it had been fixated, the infant was presented with one of the two sounds. While looking at two empty frames, the infant listened for 8 s. The *critical location* was defined by the empty frame, which had previously contained the toy associated with that sound.

Data analysis

We calculated the average total looking times to the left and right halves of the screen during test trials. Based on our previous experience with this paradigm (see Richardson & Kirkham, 2004), we chose halves of the screen as our regions of interest. Because we are measuring "looks to nothing," it is typical that there should be a wide distribution of fixation locations. Analyses have shown that smaller regions of interest such as only the frames themselves yield the same results; however, due the higher degree of noise in the signal from 3-month-olds' gaze positions, we continued with the larger region of interest.

Results and discussion

Both the 3- and 6-month-olds looked longer toward the critical location during test trials (Fig. 2). A 2 (Location: critical or noncritical) × 2 (Age) analysis of variance (ANOVA) revealed significant effects of location, $F(1,20) = 15.87$, $p < .001$, Cohen's $d = 0.53$, reflecting longer looking overall at the critical location, and age, $F(1,20) = 5.27$, $p < .05$, $d = 0.99$, reflecting longer looking overall by older infants. There was no significant interaction ($F < .01$). Planned comparisons showed that the difference between the critical location ($M = 479$ ms, $SD = 512$) and the noncritical location ($M = 254$ ms, $SD = 302$) was significant for 3-month-olds, $F(1,8) = 5.41$, $p < .05$, $d = 0.54$. Of the 9 infants, 8 showed this pattern of looking (Wilcoxon's $z = 2.31$, $p < .05$). The same was true of 6-month-olds. Looking times to the critical location ($M = 858$ ms, $SD = 459$) were significantly longer than those to the noncritical location ($M = 626$ ms, $SD = 297$), $F(1, 12) = 10.77$, $p < .01$, $d = 0.60$. Of the 13 infants, 10 followed this looking pattern ($z = 2.69$, $p < .01$).

Infants' looking time during test can appear to be short in comparison with the absolute time allowed for the test trials. This was due to the fact that there was nothing on the screen, other than the white frames, during the test trials. It took only a few fixations for infants to explore the screen and find it to be empty. Crucially, however, these exploratory fixations were directed toward the critical port, replicating our original finding (Richardson & Kirkham, 2004) in 6- and 3-month-olds.

Experiment 2

What role do visual cues play in dynamic spatial indexing? In this paradigm, it is possible that infants are learning sound–location associations without encoding anything about the visual features beyond the place that they appear. In Richardson and Kirkham's (2004) version of the experiment for adults, participants saw identical spinning crosses appear in each of the frames in turn as they listened to pieces of spoken information. In that case, they re-fixated the empty frames when recalling the information. If infants have the ability to spatially index in exactly the same way, they will be able to associate two sounds with two locations even when a visually identical toy appears in the two locations.

There is good reason to think that infants might be unconcerned with the features of the toys in this task. Although infants younger than 10 months of age can remember the visual features of an object, violation of expectation experiments suggest that they individuate objects on the basis of spatiotemporal cues rather than visual features (Leslie, Xu, Tremoulet, & Scholl, 1998; Xu & Carey, 1996). So if it is the case that spatial indexing only requires that objects be individuated by spatiotemporal cues, then infants should be able to succeed when a single set of visual features appears in one location and then (discontinuously) appears in another location.

We investigated a minimal cue hypothesis with a version of Experiment 1 in which the structure of the location and sound cues was identical but a single set of visual cues was presented throughout. In this *one toy* condition, infants only ever saw a single toy appearing in each of the two locations moving to two different sounds. We observed performance in 6- and 10-month-olds.[1]

Method

The design of this experiment was identical to that of Experiment 1 except that only one toy was presented during familiarization trials.

Participants

In total, 13 full-term 6-month-olds (6 female and 7 male, mean age = 6.1 months, $SD = 0.3$) and 16 full-term 10-month-olds (8 female and 8 male, mean age = 10.2 months, $SD = 0.4$) comprised the final sample. An additional 6 6-month-olds and 9 10-month-olds were observed but not included in the analyses because of fussiness or poor calibration.

Stimuli

One toy was selected randomly and paired with two different sounds. These movies appeared consistently in the two different frames.

Results and discussion

In the one toy condition, there were no reliable differences between looking toward the critical location and looking toward the noncritical location for 6-month-olds, but there were for

[1] To preempt our results, we ran the 6-month-olds first and found no evidence for successful spatial indexing in that age group. Because there was no reason to expect 3-month-olds to succeed at this (presumably more difficult) task, we instead chose to test 10-month-olds. For ease of exposition, we describe these sequential experiments here as conditions in a single experiment.

10-month-olds (see Fig. 2). Whereas 6 of the 13 6-month-olds looked longer toward the critical location ($z = 0.80$, *ns*), 11 of the 16 10-month-olds looked longer ($z = 2.33$, $p < .05$). A Location × Age ANOVA revealed a significant main effect of age, $F(1,27) = 5.54$, $p < .05$, $d = 0.83$, reflecting longer looking overall by older infants. The effect of location was not statistically significant, $F(1,27) = 1.53$, *ns*, but there was a significant interaction between age and location, $F(1,27) = 8.35$, $p < .01$. Analysis of 6-month-olds' data revealed no significant effect of location, $F(1,12) = 1.45$, *ns.* In contrast, 10-month-olds looked longer at the critical location ($M = 990$ ms, $SD = 545$) than the noncritical location ($M = 752$ ms, $SD = 752$), $F(1,15) = 9.72$, $p < .01$, $d = 0.46$.

A comparison of data from the 6-month-olds in Experiments 1 and 2 showed a significant interaction between toy condition (two toys vs. one toy) and looks to the critical and noncritical locations, $F(1,24) = 8.20$, $p < .01$. This provides evidence against the minimal cue hypothesis. For this age group, DSI is dependent on the association of distinct visual features with sound–location pairings. By 10 months of age, however, indexing appears to be accomplished from associating sounds with locations even in the absence of distinct objects.

Experiment 3

The failure of 6-month-olds in the one toy condition suggests that visual cues do play some role in dynamic spatial indexing at that age. We explored that role further in Experiment 3. Sound and location pairings were once more kept the same, but 6- and 10-month-olds were presented with *six toys* across the two locations.[2] If the minimal cue hypothesis is correct, then this continual variation in visual cues will not be relevant to learning of sound–location pairings.

Method

Participants

In total, 18 full-term 6-month-olds (11 female and 7 male, mean age = 6.2 months, $SD = 0.3$) and 18 full-term 10-month-olds (8 female and 10 male, mean age = 10.2 months, $SD = 0.4$) comprised the final sample. An additional 7 6-month-olds and 4 10-month-olds were observed but not included in the analyses because of fussiness or poor calibration.

Stimuli

In the six presentation trials of each block, six different toys were shown, and the sound and location pairings remained consistent.

Results and discussion

An Age × Location ANOVA revealed a reliable main effect of age, $F(1,34) = 5.66$, $p < .05$, $d = 0.70$, the result of longer looking overall by the older infants. The main effect of location was not statistically significant, $F(1,34) = 3.36$, *ns,* nor was the interaction, $F(1,34) = 0.44$, *ns.* A planned comparison revealed that 10-month-olds looked significantly longer at the critical location ($M = 993$ ms, $SD = 538$) than the noncritical location ($M = 808$ ms, $SD = 562$) in this six toys condition, $F(1,17) = 4.58$, $p < .05$, $d = 0.34$. Of the 18 10-month-olds, 12 followed this looking pattern ($z = 1.82$, $p < .07$). Analysis of the 6-month-olds' data, in contrast, found no significant difference, $F(1,17) = 0.52$, *ns*, between looks to the critical location ($M = 604$ ms, $SD = 417$) and looks to the noncritical location ($M = 518$ ms, $SD = 388$), with 10 of the 18 6-month-olds looking longer toward the critical location ($z = 0.76$, *ns*). An analysis comparing data from 6-month-olds in Experiments 1 and 3 revealed a significant interaction between the number of toys and looks to the critical and noncritical locations, $F(1,27) = 8.20$, $p < .01$, demonstrating that indexing is disrupted when sound–location pairings are associated with six inconsistent sets of visual features. It is unlikely that 6-month-olds did not provide evidence of

[2] To be confident that we provided conditions that were sufficiently sensitive to reveal evidence of indexing by 6-month-olds, we chose to increase the number of participants we ran in each condition.

indexing because of overloaded working memory for visual features, or an inability to discriminate the objects, given that 6-month-olds also fail when there is only one toy (Experiment 2) and 3-month-olds succeed when there are two toys (Experiment 1). However, 10-month-olds provided evidence for DSI under these conditions.

Experiment 4

We previously argued that dynamic spatial indexing is facilitated by the consistent association of distinct visual cues and sounds. We claimed that the minimal cue hypothesis could be rejected because spatiotemporal cues alone (the appearance of discrete events in the two ports with no connecting motion) did not appear to be sufficient to perform spatial indexing. However, it could be the case that the spatiotemporal cues here are simply too weak. Perhaps the findings of Experiment 2 could be explained if infants were forming only one object representation and associating it with both sounds. In other words, the infant sees a toy appear in one port and then assumes that the same toy has transported to the other port. To test this hypothesis, we ran a *constant toys* condition in which strong spatiotemporal constraints dictated that there were two objects.[3] The experiment was identical to Experiment 2, the one toy condition, except that here the two identical toys both remained on the screen throughout all of the presentation trials. Only one toy at a time moved with a particular sound and so was associated with a particular location. While one toy moved in time to the sound, the other (identical) toy remained stationary in the other frame. The 6-month-olds should succeed at spatial indexing in this case if spatiotemporal constraints, rather than visual features per se, allow the correct number of object representations to be formed. The multiple cue hypothesis, in contrast, predicts that 6-month-olds would continue to fail here, as in Experiment 2, because infants at that age require covarying visual features to learn spatial–auditory pairings.

Method

Apparatus

Data were gathered with a Tobii 1750 eye-tracker (http://www.tobii.com) with a 17-inch built-in monitor. Stimuli were presented using Tobii's ClearView AVI presentation software. Every other aspect of the setup and stimuli was identical to the previous three experiments.

Participants

In total, 16 full-term 6-month-olds (7 female and 9 male, mean age = 5.9 months, $SD = 0.5$) participated.

Results and discussion

There were no reliable differences between looking times for the critical location and those for the noncritical location, $t(14) = 0.32$, *ns* (Fig. 2). Of the 16 6-month-olds, 9 looked longer toward the critical location ($z = 0.27$, *ns*).

Our results align with more recent findings that infants individuate objects from visual attributes such as shape and size as young as 4.5 months if not required to retain information across trials (Wilcox, 1999) and that 4-month-olds detect changes in features of faces and toys when these stimuli are displaced behind occluders across trials (Mareschal & Johnson, 2003). Recent infant work (e.g., Surian & Caldi, 2009) proposed that infants under 1 year of age can use dynamic features to individuate objects, placing the target objects into different categories based on their characteristic movement (i.e., agent or inanimate object).

These results allow us to reject the minimal cue hypothesis. For 6-month-olds, the contents of visual cues are relevant to DSI. How exactly are they relevant? One possibility is that co-occurrences of visual and spatial information are supporting the individuation of the objects, allowing two different

[3] We thank an anonymous reviewer for this suggestion.

sounds to be associated with two memory representations. Another possibility is that the objects are always individuated, even with minimal cues, but co-occurrences between multiple cues make the representations more robust in memory (e.g., Feigenson, 2005; Oakes, Kovack-Lesh, & Horst, 2009). In each case, however, infants are encoding visual features in indexing situations and are using this information to predict the appearance of an event.

General discussion

To learn from a noisy complex world, infants must recognize and combine appropriate clusters of sensations that will produce useful and reliable representations. The relation between cues from different modalities can be a blessing and a curse in this endeavor. On the one hand, our world is layered with perceptual redundancies that help to guide attention (e.g., Bahrick & Lickliter, 2000; Lewkowicz, 2000) and support detection of probabilistic information (Kirkham et al., 2007). Many kinds of information (e.g., the location or frequency of an event) can be conveyed simultaneously in visual and auditory information, and by 4 to 6 months of age infants detect associations between arbitrary sounds in synchrony with visual events (e.g., Bahrick, 2001). On the other hand, complex relations between cues can be a distraction when the relevant information is contained in a small subset of cues. For example, when categorizing tools, variation in color might be irrelevant. This trade-off between useful cue redundancy and irrelevant cue variation has been well studied in concept acquisition (e.g., Quinn, 2004) and speech perception (Kuhl, 2004). It is not yet clear how the same trade-off is made during other perceptual and cognitive tasks such as keeping track of objects in the world.

The current research showed that infants as young as 3 months could successfully index multimodal events. At 6 months of age, that ability rests on the structure of the visual cues. Even though the task could be performed regardless of the content of the visual cues, infants were able to index events only when the regularity of the visual cues matched the regularity of the auditory cues. In contrast, 10-month-olds appeared to learn sound–location pairings when the visual cues were uninformative because they were constant (one toy condition) or uninformative because they were frequently changing (six toys condition).

Converging evidence of this developmental shift in the use of multiple cues comes from the domain of statistical learning. In an experiment reported by Kirkham et al. (2007), infants were familiarized to shapes that appeared one at a time in six different locations of a grid. The sequence of locations was structured by transitional probabilities (following Kirkham, Slemmer, & Johnson, 2002). Only 11-month-olds showed evidence of learning a spatial sequence of identical red circles. But when unique colors and shapes were shown, 8-month-olds succeeded too. These results show that infants' learning depends on an interaction between their age and the degree of coherence between spatial and non-spatial cues.

These results are consistent with a wealth of evidence that multiple cues scaffold learning during infancy and that redundant information across modalities recruits infant attention and enhances cognitive development (Bahrick & Lickliter, 2000). Our experiments reveal preliminary evidence of an interesting developmental trajectory. Of course, this finding will benefit from work within more natural contexts and across broader categories of stimuli, but we suggest that whereas younger infants appear to learn best when cues across stimulus modalities are redundant or otherwise consistent, older infants can perhaps tolerate reduced amounts of information, identifying patterns from multiple dimensions despite distractions (e.g., Kirkham et al., 2007; Pereira & Smith, 2009; Rakison & Butterworth, 1998; Wu, Gopnik, Richardson, & Kirkham, 2011; Younger & Cohen, 1986).

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