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How to Compare Apples and Oranges: Infants' Object Identification Tested With Equally Salient Shape, Luminance, and Color Changes

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What kind of featural information do infants rely on when they are trying to recognize a previously seen object? The question of whether infants use certain features (e.g., shape or color) more than others (e.g., luminance) can only be studied legitimately if visual salience is controlled, as the magnitude of feature values—how noticeable and interesting they are—will affect results. We employed a novel methodology, interdimensional salience mapping, that allowed us to quantify and calibrate salience changes along shape, luminance, and color feature dimensions. We then compared 9-month-old infants' identification of objects, employing feature changes that were equally salient. These results show that infants more readily identify objects on the basis of color and shape than luminance. Additionally, we show that relative salience changes rapidly in infancy—in particular, we found significantly higher salience thresholds for color in younger (6.5-month-old) infants—but that individual differences within an age group are remarkably modest.

Imagine that you are at a cocktail party, drinking a glass of wine. You put down your glass on a crowded table, get distracted for a moment in conversation, and then look back to retrieve your glass. Which one is yours? You might try to exploit spatial information, or you might rely on featural information: the shape of the glass, the color of the wine, or how much you had left. This issue of object identification by featural as opposed to spatiotemporal information has been at the fore-

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front of research on infant cognitive development since Xu and Carey's (1996) seminal paper. This article is an attempt at a finer analysis of infants' relative use of various feature dimensions for object identification; that is, to tell "whether what we see now was different, similar or the same as what we once saw" (Gratch, 1976, p. 173). Here we address whether infants rely more on shape, color, or luminance. Are you better off if you are the only one drinking white wine, or if everyone else is drinking from martini glasses?

INTERDIMENSIONAL SALIENCE MAPPING

The goal of this article is to evaluate infants' relative identification abilities for luminance, color, and shape; it is not our goal to just produce an existence proof that infants are able to identify objects on the basis of a particular feature at a certain age. This poses a challenge experimentally, because it is not obvious how to compare abilities across feature dimensions. If infants notice when an object changes from a square to a star shape (say, while briefly occluded), but fail to note when a yellow square changes to a blue one, does that mean that their identification abilities are better for shape changes than for color? What if we had chosen a shape change of disk to oval, or a color change from gray to hot pink? In the influential line of research conducted by Wilcox and colleagues (Wilcox, 1999; Wilcox & Chapa, 2004; Woods & Wilcox, 2006) infants seemed to exploit information about the boundaries of visual objects, like shape and size, developmentally before they are able to use surface features, such as pattern or color. Similarly, Kaldy and Leslie (2003) showed that 9-month-old infants used shape, but not color, for identifying objects. It is important to acknowledge, however, the difficult choices experimenters face when choosing objects, or to-be-detected changes in objects. Kaldy and Leslie noted the need to account for the *visual salience* of changes—how noticeable and interesting they are—and carried out a limited salience calibration in a subsequent study that actually showed that when objects were properly calibrated, infants could identify objects by virtue of color at 6.5 months of age, while failing to identify on the basis of luminance (Kaldy, Blaser, & Leslie, 2006).

In this article, we put forward an innovative, general methodology—interdimensional salience mapping (ISM)—that provides a method for calibrating visual salience between feature dimensions. This method can be used for surface and nonsurface features, and for more than two dimensions in parallel (both advantages over the method used in Kaldy et al., 2006). The notion of visual salience was popularized by Koch and Ullman (1985), who used a salience map to describe a winner-take-all network where information from various topographic feature maps competes. Related concepts have emerged as an attention map (Mozer, 1991), a priority map (Ahmad & Omohundro, 1991), and a selective tuning mechanism (Tsotsos et al., 1995). We define *salience* as the visual system's real-time assessment of the behavioral relevance (current importance) of information in the scene—a prioritization that drives attention allocation and consequent eye movements.

Recent research on visual salience has focused primarily on studies of adults, and we believe that infant research benefits from forging connections with adult psychophysics and psychophysical methods (see Aslin, 2007; Aslin & Fiser, 2005; Kellman, 2001). In the infancy literature, quantifying visual salience attracted some attention in the 1970s and early 1980s (Banks & Salapatek, 1981; Ruff & Turkewitz, 1979; Welch, 1974). These studies showed systematic relations between visual preference and feature intensity or complexity. More recently, Dannemiller and his colleagues have been conducting pioneering research on the effect of bottom-up factors on infant attention (Dannemiller, 1998, 2000; Ross & Dannemiller, 1999). They showed that as early as 7 weeks, sensitivity for a small moving stimulus can be significantly influenced by the simultaneous presence of competing targets of attention in the visual field (Dannemiller, 2000), and at 3 months of age, salience effects based on luminance and color contrast contribute to orienting (Dannemiller, 2002; Ross & Dannemiller, 1999). On the other hand, there is also a wealth of studies comparing the use of different features—in very young, 3- to 5-month-old infants—in cognitive processes such as visual attention, working memory, and long-term memory (see Cohen, 1973; Rovee-Collier, Schechter, Shyi, & Shields, 1992; Saayman, Ames, & Moffett, 1964; Steele & Pederson, 1977). Our goal is to connect these two lines of research: quantify differences in visual salience that can affect results of studies using classical cognitive paradigms.

To develop ISM, we adapted the classic forced-choice preferential-looking method that has proved exceptionally useful in perceptual threshold measurements (Teller, 1979; for a review, see Teller, 1997). This is our operational definition of relative salience (the salience of a region is always relative to its context): The object with the higher salience is the one that is preferred; in other words, the one that wins the first look when placed in head-to-head competition (see Civan, Teller, & Palmer, 2005, for a similar method). By manipulating the features of one of these objects to render it more and more salient than its competitor, and therefore more and more likely to grab the first look, we can produce a psychometric function of salience. By doing this for various feature dimensions, we can then choose stimuli that have known salience relationships. These stimuli can then be employed fairly in cognitive tests of learning, memory, search, or, as in our case, relative object identification abilities.

To accomplish this comparison for our three feature dimensions of shape, luminance, and color, we needed to generate a set of four objects: a baseline object and three comparison objects, with one that differs from the baseline only in shape, another that differs only in luminance, and a third that differs only in color (see Figure 1a). Critically, the salience differences between the baseline and the three comparisons should be all equal. Experiment 1A is the ISM salience calibration itself, and Experiment 2 is the subsequent identification study for shape, luminance, and color. Experi-

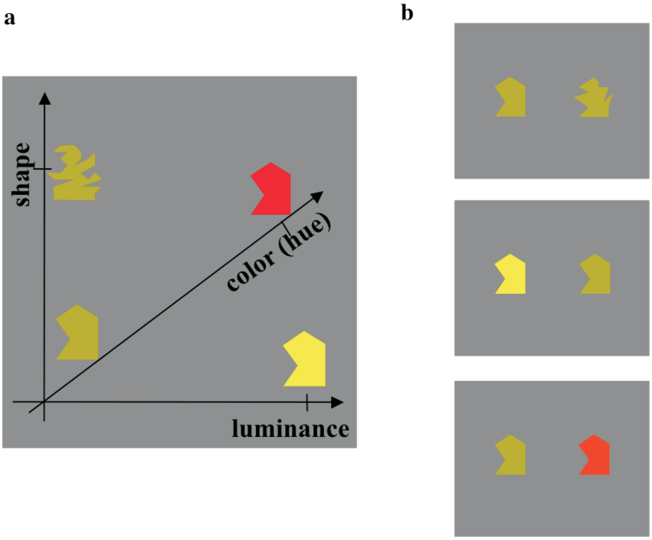

FIGURE 1 Interdimensional salience mapping: (a) The purpose of ISM is to find iso-salient differences along feature dimensions; here shape, luminance, and color comparisons are shown relative to a common baseline object. (b) Sample preferential looking displays showing baseline versus a randomly chosen shape, luminance, and color comparison from Experiment 1A. (Please note that these reproductions do not exactly match the appearance of actual experimental stimuli. Figure is provided in color online.)

ment 1B looks for developmental changes by repeating Experiment 1A with younger infants. Experiment 1C evaluates relative salience for groups versus individuals.

EXPERIMENT 1A: SHAPE, LUMINANCE, AND COLOR SALIENCE MAPPING

Methods

Participants. ISM was divided into two parts: Shape and luminance calibration trials were run in mixed blocks with one group of infants, and color trials were run mixed with a limited set of luminance trials in a second group of infants.[1] For

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[1] Our pilot studies have shown that we cannot collect sufficient data per feature and per infant participant if we test three different featural dimensions in mixed blocks. Data from these luminance trials produced a statistically indistinguishable psychometric curve to the luminance results in the shape and luminance mixed blocks (see Figure 2a, gray line; for further discussion see "Stimuli and Procedure" section). Further, this supports our assumption that there is no interaction between different dimensions in our paradigm.

shape andluminance calibration, 15 healthy, full-term, 9-month-old (age = 255 days–285 days, $M = 263.4 \pm 10.0$ days) infants (8 girls) participated. For color calibration, 8 healthy, full-term 9-month-old (age = 255 days–285 days, $M = 270.9 \pm 11.8$ days) infants (5 girls) participated. Eight additional infants were tested but excluded due to fussiness ($n = 5$) or experimental error ($n = 3$). Parents of participants in all of the studies reported here were recruited from a commercially available database of the greater Boston area and received a small gift for participation. None of the infant participants had parents with colorblindness.

Apparatus. Infants sat on their parent's lap approximately 40 cm away from a 21-in. LCD monitor in a dimly lit, isolated testing area. Stimuli were computer generated and controlled, using Macromedia Director and an Apple Macintosh G5. A concealed video camera recorded infants' behavior. Parents were instructed to keep their eyes closed and not to interact with their infants during testing.

Stimuli and Procedure. Displays consisted of two objects presented on a uniform, gray background (see Figure 1b). Stimuli were calibrated using a Pantone Spyder2PRO colorimeter. The gray background and the baseline object (a yellowish angular shape) had CIE [x, y, Y] coordinates of [0.35, 0.35, 22.8] and [0.43, 0.48, 32.2], respectively. In shape trials, the baseline was paired with an identically colored, but more complex shape comparison. The five shape comparisons were generated by increasing the perimeter and number of edges, while holding area constant, yielding the following shape estimate values (perimeter^2/area; see Zusne, 1970): baseline = 19, S1 = 28, S2 = 38, S3 = 49, S4 = 61, S5 = 75. (There are, of course, innumerable ways to define shape changes, and we are not making any deep claims about this manipulation. This manipulation has the advantage of being quantitative and maintaining area, topology, and family resemblance.) In luminance trials, the baseline object was presented simultaneously with an identically shaped, but brighter yellow comparison object. The five luminance comparison objects had the following CIE coordinates: L1: [0.43, 0.48, 47.8], L2: [0.43, 0.48, 63.3], L3: [0.43, 0.48, 78.4], L4: [0.43, 0.48, 94.4], L5: [0.43, 0.48, 110.3]. For color trials, color manipulations were created by increasing the redness of the object, moving from yellow through orange to red (comparisons C1–C5), while maintaining isoluminance[2] to the baseline (i.e., a hue change).[3] All objects subtended 4° of visual angle and were spaced 8° apart. The position of the comparison versus baseline (left–right) was randomized across trials. The intensity of the comparison object was chosen randomly, trial-to-trial, from the five predetermined levels (see Figure 2).

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[2] Isoluminance was calibrated using the minimum motion technique on adults, which provides a valid estimate of infant values (Pereverzeva, Chien, Teller, & Palmer, 2002).

[3] Studies of spontaneous hue preferences have shown that infants prefer red to yellow (Bornstein, 1975; Zemach, Chang, & Teller, 2007).

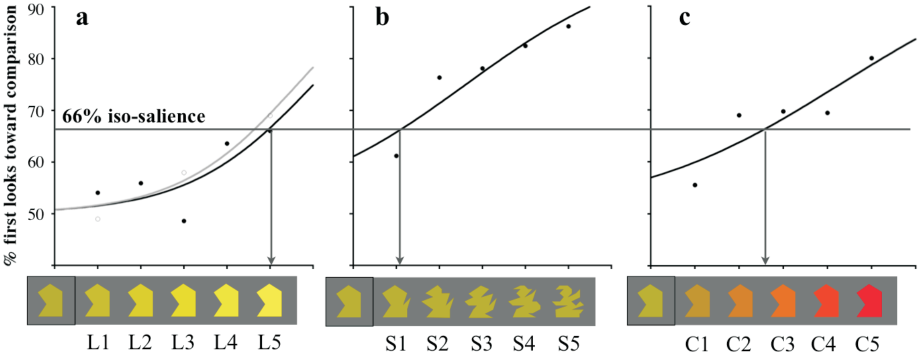

FIGURE 2 Psychometric functions of salience determined from preferential looking experiments with 9-month-old infants. The x-axis shows the feature "intensity" of comparison objects along the (a) luminance, (b) shape, and (c) color dimensions. The y-axis shows the percentage of trials in which infants' first look was directed toward the comparison object. The data were fit by a cumulative normal function (shape, $R^2 = 0.86$; luminance, $R^2 = 0.64$; color, $R^2 = 0.83$). An iso-salient preference value was established at a 66% iso-salience level. This iso-salience level defined three objects (luminance, shape, and color; indicated by arrows) that had equally salient differences from baseline. Each of these comparison objects was then paired with the baseline object in the object identification tests of Experiment 2. (Luminance trials in the color and luminance mixed blocks resulted in a psychometric function statistically indistinguishable from that obtained from the shape and luminance mixed blocks; see gray curve in Figure 2a. Figure is provided in color online.)

A sound cued the beginning of each trial. The two objects—baseline and comparison—were then presented simultaneously for 2 sec, after which the trial ended. During the 1-sec interval between trials, a black 4° × 4° fixation cross was presented in the center of the otherwise blank screen. Infants' eye movements were coded for each 2-sec trial. The dependent variable was the direction of the infants' first look (left–right) for each trial.[4]

A maximum of 56 trials per infant were run: The first 2 trials were warm-up trials in which two baseline objects were presented, with one of them rotating in place for 2 sec; 50 were test trials; and 4 were attention-getting trials (identical to the warm-up trials) presented after every 10 test trials. In the mixed blocks of

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[4] We argue this measure is the most valid if salience is understood as a prioritization in visual processing (e.g., Koch & Ullmann, 1985). We prefer this to total looking time measures, as extended viewing potentially allows for the confounding influences of memory and other cognitive factors to have time to come into play. However, for comparison, we recoded the entire data set of Experiment 1 by relative total looking time per trial. (Note that the length of each trial was relatively short, only 2 sec.) The results showed that the concordance between coding relative looking time and direction of first looks is in the same range as the interobserver reliability for coding first looks (94.1% concordance). Because they yielded very similar results, we felt further justified to use the cleaner, theoretically more motivated choice of first looks.

shape and luminance trials, the 50 test trials consisted of five levels of comparison each for shape and luminance with five trials per object. In the color blocks, seven trials per comparison level were presented. To present a varied stimulus set to the infants and to demonstrate that dimensions do not interact in the mixed-block design, we included a smaller number of luminance trials mixed in with the color trials (three comparisons, 15 trials total per participant). Data from these trials are presented in Figure 2a (gray curve), and was not significantly different (for data analysis and detailed results, see later) from luminance trials (black curve). Offline, two independent, trained observers blind to the experimental conditions encoded infants' first look from the video recordings. Trials for which there was a disagreement between the two observers were excluded (approximately 5% of all trials).

Results

All of the infant participants had valid responses (left–right looks where the two observers were in agreement) in at least 15 of the 50 trials. In the mixed blocks of shape and luminance, a total of 559 test trials were collected: 276 shape and 283 luminance trials. The average number of completed trials was 37.3 per infant. For color calibration, a total of 372 trials were collected: 234 color test trials and 138 luminance test trials. The average number of completed test trials was 46.5 per infant. These data were fit with a cumulative normal, and the resulting psychometric functions appear in Figure 2. The horizontal axis represents the comparison intensity. The vertical axis represents the percentage of trials where the comparison was preferred (% of first looks toward comparison).

To compare whether luminance trials collected in the two different types of mixed blocks (mixed with color vs. shape) yielded different results, we conducted a repeated measures logistic regression analysis (see, e.g., Hardin & Hilbe, 2001). Looks toward the comparison as a binary variable was our dependent variable, intensity and trial were within-subjects variables, and group (shape/luminance vs. color/luminance mixed blocks) was the between-subject variable. The model included the main effects of group and intensity and their interaction. The main effect of group was not significant, Wald's $\chi^2(1, N = 471) = 0.059$, $p = .808$, but the main effect of intensity was, Wald's $\chi^2(4, N = 471) = 10.793$, $p = .029$. The interaction between the two factors was not significant, Wald's $\chi^2(2, N = 471) = 1.239$, $p = .538$.

Discussion

The pattern of results shows that when the comparison differed only slightly from the baseline, infants tended to look at the two equally, whereas in those trials where the comparison had a more complex shape, was much brighter, or was clearly redder than the baseline, infants tended to look at the comparison first.[5]

We were now able to determine the three comparison objects—shape, luminance, and color—needed for the identification task in Experiment 2. We chose a 66% iso-salience preference level from the three psychometric functions (see Figure 2).[6] The objects so defined had the following properties: (a) The baseline and the more complex shape comparison differed only in shape; (b) the baseline and the brighter yellow comparison differed only in luminance; and (c) the baseline and the more reddish comparison differed only in color; but crucially, (d) the differences in salience between the baseline and each of the three comparisons were equal (i.e., all three comparisons draw infants' first look on 66% of the trials, compared to the baseline).

EXPERIMENT 1B: SHAPE, LUMINANCE, AND COLOR SALIENCE MAPPING IN 6.5-MONTH-OLD INFANTS

The psychometric functions obtained in Experiment 1A represent group data from 9-month-old infants, but leave two questions unanswered: To what extent can data from a particular age group be applied to another age group, and to what extent are the results from a group representative of individual data? We address these two questions in Experiments 1B and 1C, respectively. Here in Experiment 1B, to explore how perceived salience changes with age, we tested younger, 6.5-month-old infants with our salience mapping paradigm. Our hypothesis was that younger infants would have higher thresholds for feature intensity manipulations, therefore

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[5] It is important to note that because each trial included the baseline, the infants saw the baseline more often than any particular comparison. Potentially then, its salience could have decreased over time, thereby increasing preference for the comparison stimuli. However, the proportion of trials on which comparison stimuli garnered the first look in the first half of a block of trials was 64%, nearly identical to the 67% in the second half. We also conducted this split-half analysis for each participant with a paired two-sample t test. The result of this test was not significant, $t(18) = 0.512, p = .615$. In case habituation was especially rapid, we compared (across all infants in the shape and luminance trials) the first successful trial (the first trial that got a legitimate look, typically the first or second trial), to the last successful trial of the same trial type (on average, Trial 36). The preference for the comparison was 69% in both cases, so there was no difference whatsoever. In a final analysis, we compared the first successful S5 trial (maximum shape comparison, on average the 12th trial), to the last successful S5 trial (on average the 40th), again across all participants. This yielded a preference for the S5 comparison of 77% and 73%, respectively (a slight trend actually in opposition to any concerns about habituation to the baseline, and in any case not significant), $\chi^2(1, N = 66) = 0.81$. We are therefore confident that the salience of the baseline did not significantly decrease over time.

[6] The choice of iso-salience level depends on one's purposes. A value too high will likely produce ceiling effects, and a value too low, floor effects. A level close to threshold—75% typically—is a standard choice. We chose the closest value to this threshold that our data set allowed—the highest preference level measured for luminance (66%) created an upper boundary.

requiring larger featural differences than older infants to achieve a particular salience difference. The experimental stimuli and procedures were the same as in Experiment 1A.

Methods

Participants. The ISM was divided into two parts: Shape and luminance calibration trials were run in mixed blocks with one group of infants, and color trials were run mixed with a limited set of luminance trials in a second group of infants (these luminance trials were not analyzed). For shape and luminance calibration, 14 healthy, full-term 6.5-month-old (age = 180 days–210 days, $M = 193.4 \pm 7.9$ days) infants (5 girls) participated. For color calibration, 10 healthy, full-term 6.5-month-old (age = 180 days–210 days, $M = 199.6 \pm 5.7$ days) infants (6 girls) participated. Ten additional infants were tested but excluded due to fussiness ($n = 8$) or experimental error ($n = 2$).

Apparatus, stimuli, and procedure. The apparatus, the stimuli, and the procedure were the same as in Experiment 1A.

Results

All of the infant participants had valid responses (left–right looks where the two observers were in agreement) in at least 15 of the 50 trials. In the shape and luminance calibration, a total of 451 test trials were collected: 226 shape and 225 luminance trials. The average number of completed trials was 32.2 per infant. For color calibration, a total of 302 color and 127 luminance test trials were collected. The average number of completed test trials was 42.9 per infant. The resulting psychometric functions appear in Figure 3. In all cases the salience functions from the 6.5-month-olds were shifted laterally relative to the functions from the 9-month-olds; using the 66% iso-salience level as in Experiment 1A, there was a trend for higher thresholds in 6.5-month-olds than 9-month-olds in all conditions (shape, 3.04 vs. 3.86; luminance, 4.93 vs. 6.22 (extrapolated); and color, 2.50 vs. 4.36).

We compared the data from this experiment to data collected from the older infants in Experiment 1A by using a repeated measures logistic regression. We used the following model in each of these analyses. Looks toward the comparison as a binary variable was our dependent variable, intensity and trial were within-subjects variables, and age group (6.5- vs. 9-month-olds) was a within-subjects variable. The model included the main effects of age and intensity and their interaction.

Looking over the entire data set, we saw that age was indeed a significant factor, Wald's $\chi^2(1, N = 1479) = 6.661$, $p = .01$, as well as intensity, Wald's $\chi^2(4, N = 1479) = 29.271$, $p = .0001$, but their interaction was not, Wald's $\chi^2(4, N = 1479) = 0.351$, $p = .986$. We could then do a more fine-grained analysis for each of the three tested features.

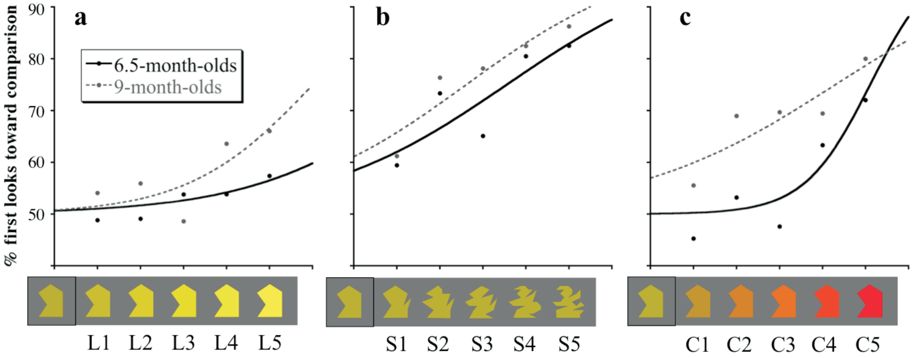

FIGURE 3 Psychometric functions of salience determined from preferential looking experiments with 6.5-month-old infants (black curves). The x-axis shows the feature intensity' of comparison objects along the (a) luminance, (b) shape, and (c) color dimensions. The data were fit by a cumulative normal function (shape, $R^2 = 0.72$; luminance, $R^2 = 0.74$; color, $R^2 = 0.85$). Data from 9-month-olds from Figure 2 is presented again here for easy visual comparison (gray dashed curves). (Figure is provided in color online.)

For luminance, the main effect of age group was not significant, Wald's $\chi^2(1, N = 510) = 0.471$, $p = .492$), but the main effect of intensity was, Wald's $\chi^2(4, N = 510)) = 10.143$, $p = .038$. The interaction between the two factors was not significant, Wald's $\chi^2(4, N = 510) = 7.199$, $p = .126$. We found similar results for shape. The main effect of age group was not significant, Wald's $\chi^2(1, N = 502) = 0.721$, $p = .396$, but the main effect of intensity was, Wald's $\chi^2(4, N = 502) = 21.735$, $p = .0001$. The interaction between the two factors was not significant, Wald's $\chi^2(4, N = 502) = 3.080$, $p = .544$. In contrast to luminance and shape however, for color, the main effect of age group was highly significant, Wald's $\chi^2(1, N = 467) = 6.475$, $p = .011$, as was the main effect of intensity, Wald's $\chi^2(4, N = 467) = 16.703$, $p = .002$. The interaction between the two factors was not significant, Wald's $\chi^2(4, N = 467) = 3.033$, $p = .552$.

Discussion

We tested younger, 6.5-month-old infants in the same salience-calibration paradigm that had been used with the 9-month-old infants in Experiment 1A. Our results show that salience functions can differ between age groups. As hypothesized, younger infants required the presentation of more extreme feature differences than older infants to achieve the same relative salience level. In particular, we found highly significant differences between age groups for color. To be concrete, in the case of color, a stimulus of level 2.5 is preferred 66% to the baseline for 9-month-olds, but registers no preference whatsoever over the baseline for 6.5-month-olds. If one were to use the level 2.5 color value in a visual working memory study, for instance, the results would be preordained to show greater memory effects for 9-month-olds, as the 6.5-month-olds would have been asked to remember a difference that they do not find salient in the first place. It is beyond the scope of this particular experiment to say definitively which feature–salience relationships are affected by age (shape and luminance threshold differences, although showing the same trend as color, were not significant)—but the results reported here are sufficient to highlight the danger of simply assuming that it is valid to use the same set of stimuli for different age groups.

EXPERIMENT 1C: INDIVIDUAL COLOR SALIENCE MAPPING

An important question is whether group ISM data, such as those presented in Experiments 1A and 1B, are an appropriate way of estimating ideal salience functions for individual infants, or whether individual differences are too large for such an application. To address this question, an additional small group of 6.5-month-old infants was tested with the same color and luminance mixed block stimuli that were used in Experiment 1A and 1B, but now over four sessions within a 2-week period so that we could gather enough data to analyze participants' individual salience functions.

Methods

Participants. Eight healthy, full-term 6.5-month-old (age = 180 days–210 days, *M* = 195 ± 10.6 days) infants (4 girls) began a series of testing sessions, but 4 of them could not complete the required four sessions within the time frame (due to parents' scheduling conflicts and illnesses). Four participants completed all four sessions: Participant A (female, 181 days at the time of the first session), Participant B (male, 193 days at the time of the first session), Participant C (male, 205 days at the time of the first session), and Participant D (female, 201 days at the time of the first session). For these participants, all four testing sessions were completed within a 2-week period. Two additional infants were tested in one initial session, but were excluded due to fussiness.

Apparatus, stimuli, and procedure. The apparatus, the stimuli, and the procedure were the same as in Experiment 1B, except that only color and luminance mixed blocks were presented.

Results

All of the infant participants had valid responses (left–right looks where the two observers were in agreement) in at least 15 of the 50 trials per session. Data from Participant A yielded a total of 133 color test trials, Participant B yielded 165 trials, Participant C yielded 143 trials, and Participant D yielded 116 trials. (The number of luminance trials collected varied between 65 and 79, which is too low to provide a reliable function; therefore this data set was not analyzed.) The resulting psychometric functions appear in Figures 4a through 4d, respectively. Figure 4e shows aggregated data from two groups: Group 1 includes data from the first testing sessions of all 8 participants tested in Experiment 1C, and Group 2 represents data

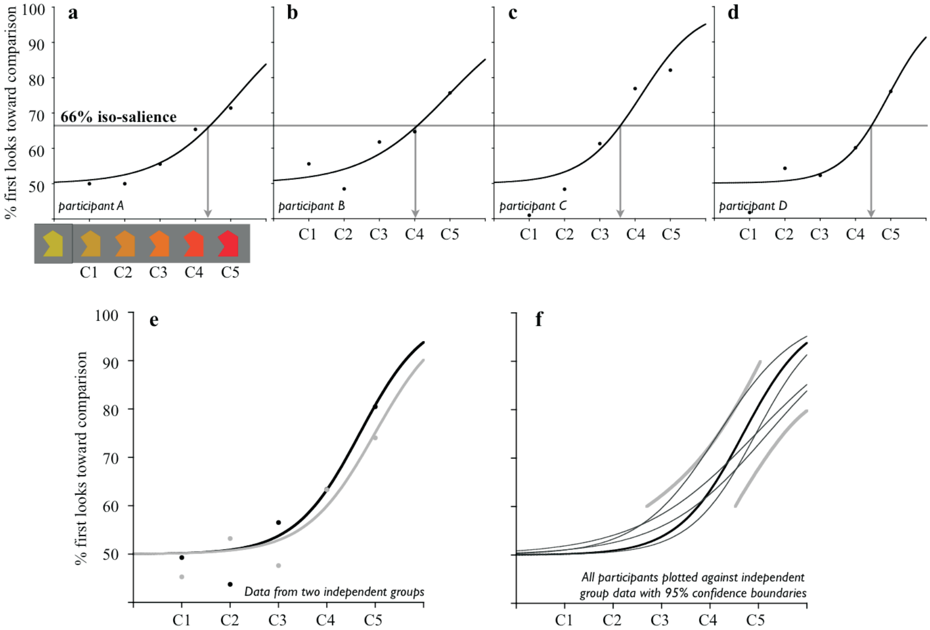

FIGURE 4 Individual color salience functions of four 6.5-month-old participants contrasted with data from two groups. Figures 4a through 4d show data from four individual participants (Participants A, B, C, and D). Preference, in terms of percentage of first looks toward the comparison is shown as a function of the comparison item's feature intensity, here along the color dimension. The data were fit by a cumulative normal (Group 1, $R^2 = 0.93$; Group 2, $R^2 = 0.88$; Participant A, $R^2 = 0.95$; Participant B, $R^2 = 0.86$; Participant C, $R^2 = 0.87$; Participant D, $R^2 = 0.87$). As expected, psychometric functions are monotonically increasing, with all four functions specifying similar comparison feature values (indicated by arrows) at the indicated 66% iso-salience preference level. Figure 4e compares salience functions from two independent groups: Group 1 (color data from the first testing session of all 8 participants tested in Experiment 1C, shown in black) and Group 2 (color data from the group of 6.5-month-olds in Experiment 1B, shown in gray). The two functions were found to be statistically indistinguishable. Finally, Figure 4f shows psychometric functions for each of the four individual participants (A–D; fine gray curves) that appeared in the top four panels, shown along with the Group 1 data (black curve). A 95% confidence interval has been drawn around the Group 1 function (Wichmann & Hill, 2001a, 2001b), for all possible threshold values ranging from 60% to 90% preference (shown as bold gray curves). All four individual psychometric functions fall within this 95% confidence interval. (Figure is provided in color online.)

collected from the separate group of 6.5-month-olds in Experiment 1B, who only had participated in one testing session (by design). These two groups, of 8 participants each and collected independently, are nearly identical and indeed statistically indistinguishable. We used a repeated measures logistic regression with the same model as in previous analyses. Looks toward the comparison as a binary variable was our dependent variable, intensity and trial were within-subjects, variables and groups (Group 1 vs. Group 2) as a between-subject variable. The model included the main effects of group and intensity and their interaction. The main effect of group was not significant, Wald's $\chi^2(1, N = 675) = 0.900$, $p = .343$, but the main effect of intensity was, Wald's $\chi^2(4, N = 675) = 23.072$, $p = .0001$. The interaction between the two factors was not significant, Wald's $\chi^2(4, N = 675) = 2.585$, $p =.630$.

Finally, Figure 4f shows psychometric functions for each of the four individual participants that appeared in the top four panels, along with the Group 1 data. Boundaries for 95% confidence have been drawn around the Group 1 function for threshold values ranging from 60% to 90% preference (shown as bold gray lines; confidence intervals were determined by the BCa bootstrap method implemented by psignifit; see Wichmann & Hill, 2001a, 2001b). Psychometric functions for each of the 4 participants fell within the 95% confidence interval around the group psychometric function.

Discussion

First of all, we successfully replicated the color calibration results of Experiment 1B (see Figure 4e). Second, Experiment 1C demonstrates that individual salience functions are quite similar to, and well represented by, group data functions: The fact that all four individual psychometric functions fall within the 95% confidence interval of the group data strongly supports the notion that individual differences are modest.

EXPERIMENT 2: OBJECT IDENTIFICATION BY SHAPE, LUMINANCE, AND COLOR

The results of the ISM in Experiment 1A yielded shape, luminance, and color comparison objects that each have equally salient perceptual differences from a common baseline object for 9-month-old infants. We can now employ these stimuli, more fairly, in a cogntive test of object identification. Here, in Experiment 2, we compared 9-month-olds' relative identification abilities—whether or not infants note changes made to these features while the object is briefly occluded—for each of these three feature dimensions.

Methods

Participants. Fifty-five healthy, full-term, 9-month-old (age = 255 days–285 days, M = 270.8 ± 10.9 days) infants (27 girls) participated. They were randomly assigned to one of the following conditions: shape study (no change [n = 9] or shape change [n = 9] outcomes), luminance study (no change [n = 10] or luminance change [n = 7] outcomes), or color study (no change [n = 11] or color change [n = 9] outcomes). Nine additional infants were tested but excluded due to fussiness.

Apparatus. The display apparatus was the same as that used for Experiment 1A, with the addition of a timing device that allowed for an online measurement of total looking time, the standard measure of infants' reaction to expected or unexpected outcomes. An online observer, trained in recording infant looking times and blind to condition, monitored the real-time video of the infant's behavior. The observer operated a button box that triggered a computer to record looking times. A sound cue signaled to the observer when the screen moved upward to reveal the object, at which point the observer held down the timing button whenever the infant looked toward the stage. Whenever the infant looked away from the stage, the observer released the button. Looking time was accumulated until the infant looked away for 2 consecutive sec, at which point the trial ended, and accumulated looking time was recorded. Recordings were later rescored offline by a second observer. If interobserver agreement between the two observers was lower than 95%, a third observer was used to break the tie (in approximately 10% of the cases).

Stimuli and procedure.

The identification tests used the violation-of-expectation method and were created using Macromedia Director. One of the objects in the pair in all of the identification experiments was always the baseline object from Experiment 1A (the yellowish angular shape). Based on the results of Experiment 1A, the following comparison objects were used. In the shape change study, the shape comparison object had three extra edges and a 20% longer perimeter than the baseline (see Figure 2a). In the luminance change study, the luminance comparison object had the following CIE [x, y, Y] coordinates: [0.43, 0.48, 110.3] (see Figure 2b). In the color change study, the color comparison object was isoluminant to the baseline and had the following CIE [x, y, Y] coordinates: [0.52, 0.43, 30.1] (see Figure 2c).

Infants were first familiarized to the baseline and the comparison object: An animated curtain was raised, and infants saw one of the objects in the pair on one side of the stage, which then moved to the other side and stayed there for 4 sec; finally, the curtain dropped (see Figure 5a). There were four such familiarization trials, two alternating exposures each of baseline and comparison. There were three sub-

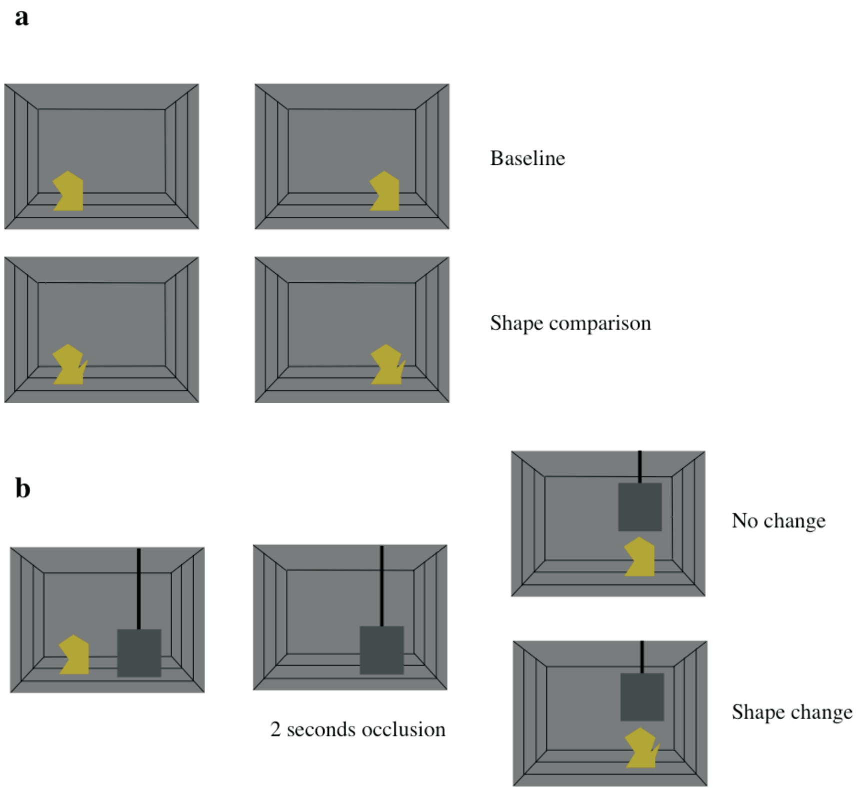

FIGURE 5 Examples of (a) familiarization and (b) test trials for Experiment 2 (here only shape study stimuli are shown). (Figure is provided in color online.)

sequent test trials,[7] separated by the animated curtain being raised and dropped in between trials. We followed a between-subject design, therefore all three test trials were identical (except for counterbalancing the two objects in the test pair). Infants in each of the no change groups saw one of the objects in the baseline or comparison pair disappear behind a screen and, once the screen was removed, saw the same object revealed. In the shape, luminance, or color change groups, one object from the pair was hidden, but the other one was revealed (see Figure 5b). Occlusion time was 2 sec. During both familiarization and test trials, the object that was presented first was alternated, and the object that started the series of trials was counterbalanced.

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[7] Our studies with similar paradigms showed that potential effects tend to appear in the first three trials (e.g., Kaldy et al., 2006; Kaldy & Leslie, 2003).

Results

In short, results of Experiment 2 show that 9-month-old infants reacted to the shape and the color change, but not the luminance change (see Figure 6). Preliminary analyses showed no effect of gender, age (infants closer to 8 vs. 10 months), or the object that was presented first prior to occlusion (baseline or comparison).

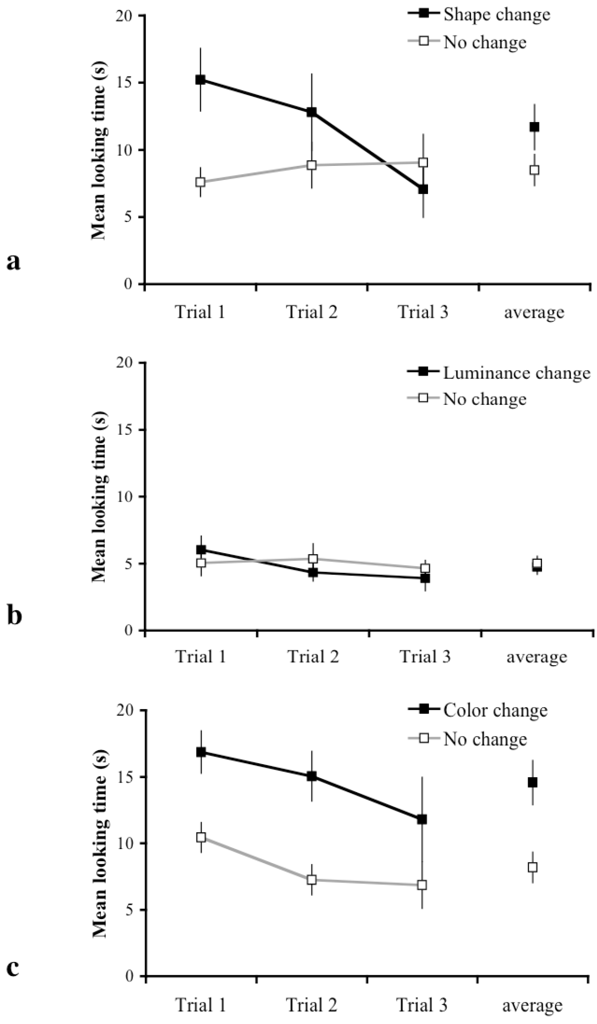

FIGURE 6 Mean looking times per trial and average looking times for the three test trials (in sec, ±SE) in (a) shape, (b) luminance, and (c) color object identification studies. Results show successful identification by shape and color, but not by luminance, in 9-month-old infants.

These factors were dropped from further analysis. Mean looking times with standard errors by condition and trial are shown in Figure 6. Looking times were analyzed in a repeated measures 3 × 2 ANOVA with trials (3) as a within-subjects factor and shape, luminance, or color change (2) as between-subject factors.

Shape change study. There was a significant main effect of trials, F(2, 32) = 1.841, p = .175. Although the main effect of the shape manipulation did not reach significance, F(1, 16) = 2.436, p =.138, there was a significant Trials × Shape Manipulation interaction, F(2, 32) = 3.359, p = .047. Infants' looking time in the shape change condition dropped faster over trials than in the no change condition. Effect size was estimated using partial η^2: Shape change accounted for 13.2% of the variance over the three test trials.

Planned comparisons examined looking times across the three test trials for the shape change versus the no change condition. Two-tailed *t* tests showed significant differences in the first, *t*(16) = 2.972, *p* = .0045, and for the average of the three test trials, *t*(16) = 1.775, *p* =.0475, but not for the second and the third test trial. Cohen's *d* was used to measure effect size: Trial 1, 1.401; Trial 2, 0.558; Trial 3, 0.311; average of three trials, 0.736.

Nonparametric tests showed similar results. Mann–Whitney's U tests (two-tailed) showed a significant difference between looking times in the shape change and the no change conditions in the first trial (*p* = .024) and a marginally significant difference in the averages of the three test trials (*p* = .062), but not for the second and the third test trials.

Luminance change study. There was no main effect of trials or the luminance manipulation, nor did trials and luminance manipulation interact (all three *F*s < 1, *ns*). Similarly, nonparametric tests did not show any significant differences.

Color change study. There was a significant main effect of trials, F(2, 36) = 4.591, p = .017. The main effect of the color manipulation was highly significant, F(1, 18) = 10.437, p = .005. There was no interaction between trials and color manipulation, F(2, 36) < 1, p = ns). Effect size was estimated using partial η^2: Color change accounted for 36.7% of the variance over the three test trials.

Planned comparisons examined looking times across the three test trials for the color change versus the no change condition. Two-tailed *t* tests showed significant differences in the first, *t*(18) = 3.361, *p* = .003, and second trial, *t*(18) = 3.704, *p* = .002, and for the average of the three test trials, *t*(18) = 3.231, *p* = .005, but not for the third test trial. Cohen's *d* was used to measure effect size: Trial 1, 1.490; Trial 2, 1.629; Trial 3, 0.629; average of three trials, 1.623.

Nonparametric tests showed similar results. Mann-Whitney's U tests (two-tailed) showed a significant difference between looking times in the color change and the no change conditions in the first (p = .004) and the second trial (p = .002) and for the averages of the three test trials (p = .006), but not for the third test trial.

Discussion

The main result of this object identification experiment showed that infants noted shape and color changes made to briefly occluded objects, while failing to react to changes in luminance. Importantly, this comparison of relative identification abilities across these three dimensions was made fair by calibrating, through ISM in Experiment 1A, the changes in object appearance to be equally salient.

GENERAL DISCUSSION

By employing an innovative method—ISM—we were able to calibrate the amount of physical change an object required along different feature dimensions (here, shape, luminance, and color) to generate equally salient changes to the object's appearance. We could then pit these calibrated objects against one another in fairer tests of infants' relative identification abilities. Results from these tests show that 9-month-olds can better identify (i.e., note changes made to a briefly occluded object) on the basis of color or shape, as opposed to luminance.

ISM not only allows comparisons between various feature dimensions, but also between age groups. If fair comparisons are to be made between the identification abilities of younger versus older infants, for instance, one cannot use the same physical magnitude changes (e.g., the same pair of toys) for both groups. What might be a sufficiently salient change for a 9-month-old is likely less to be so for a 6.5-month-old. In Experiment 1B, we showed that relative salience is age dependent, with younger infants requiring larger perceptual differences to achieve particular salience differences: For instance, the higher salience color stimulus that 9-month-olds preferred over baseline did not register any preference whatsoever for 6.5-month-olds. On the other hand, in Experiment 1C we saw that infants within an age group show remarkably modest individual differences in their salience functions and can therefore be well represented by group data.

Importantly, our assessment of relative identification ability was legitimate because ISM allowed us to calibrate our tests to be equally difficult. If we had not conducted a calibration, and had chosen different values, say, by chance, a more intense luminance change, but a more subtle shape change, we might very well have found the opposite pattern of results than those reported here. In fact, preliminary results from an ongoing study in our laboratory indicate that infants can identify on the basis of luminance using these same tests if the luminance change is made unfairly large. It is worth restating here that our goal was to assess the relative use of feature information, not whether identification based on this or that feature is possible at all. When presented with a challenging identification task, with equally salient feature changes to choose from, what will infants rely on for identification?

Identification tests like those we used here require both that an infant remember a previously seen object during the occlusion interval and that he or she compare that remembered object to the proximal one. This comparison determines, again as Gratch (1976) noted, "whether what we see now was different, similar or the same as what we once saw" (p. 173). In particular, visual working memory—the mechanism that allows for the temporary maintenance and manipulation of task-relevant visual information (Gazzaniga, Ivry, & Mangun, 2002)—is responsible for the storage of the initially presented object and provides the domain in which these short time span before-and-after comparisons are carried out. (Infants' visual working memory has been studied for objects, locations and serial order; for a review, see, e.g., Reznick [2007], and for an innovative new paradigm, see Ross-Sheehy, Oakes, & Luck [2003].) It is possible that the results reported here reflect biases in visual working memory itself; that is, that memory is worse for luminance than shape or color. However, our preferred interpretation is that our results reflect biases in object cognition, in this case, in the identification process itself. (These two explanations, of course, are not mutually exclusive.) In other words, an infant might have a robust memory for luminance information, but because it is a relatively weak indicator of object identity, such changes are deemed relatively uninteresting in these sorts of before-and-after identification tests. Small shape changes, on the other hand, are more likely to indicate identity changes and are therefore more notable (and noted) events. Although further tests will be required to resolve this issue, the results of Wilcox (1999) and Woods and Wilcox (2006), as they show similar biases with a different task (individuation as opposed to identification), support this interpretation.

The pattern of results in Experiment 2, with color and shape relied on more for object identification than luminance, is consistent with our working hypothesis that the more diagnostic features of objects are emphasized in identification. This ecological principles hypothesis is motivated primarily by considering the conditions of objects in natural scenes: Which features are most likely to be the defining characteristics of an object? Ecological principles allows for a principled standpoint from which to make predictions about infant object identification, but can only be a working hypothesis, as research on the statistical properties of natural scenes (Rosenholtz, Li, & Nakano, 2007) and formal modeling of objects' feature space (Feldman & Tremoulet, 2006), from which the "most likely defining characteristics of an object" will be determined, are ongoing. There is an emerging consensus, though: Shape and color, for instance, are thought to be relatively stable, diagnostic features, but luminance is not. A lemon can undergo quite a range of lightness changes and still remain a lemon, but modest changes in hue or shape can quickly render it a lime or grapefruit. (Interestingly, our present results show an even greater use of color than shape for identification, but we feel it is premature to speculate on this before further tests and further consideration of analyses of natural scenes.) These results dovetail with previous work that showed use of color (Wilcox [1999] found evidence for the use of color in an object individuation task at 11.5, but not at 7.5 months of age), and work that showed failures to use luminance (Kaldy et al., 2006; for similar results, see Woods & Wilcox, 2006).

In short, ISM helps formalize the elusive concept of salience—a concept that often is invoked but has not been sufficiently quantified and controlled in developmental psychology—and provides a methodology for legitimately comparing infants' abilities between age groups and feature dimensions; in other words, a method for comparing apples and oranges.

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