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Covariation of Color and Luminance Facilitate Object Individuation in Infancy

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The ability to individuate objects is one of our most fundamental cognitive capacities. Recent research has revealed that when objects vary in color or luminance alone, infants fail to individuate those objects until 11.5 months. However, color and luminance frequently covary in the natural environment, thus providing a more salient and reliable indicator of distinct objects. For this reason, we propose that infants may be more likely to individuate when objects vary in both color and luminance. Using the narrow-screen task of Wilcox and Baillargeon (1998a), in Experiment 1 we assessed 7.5-month-old infants' ability to individuate uniformly colored objects that varied in both color and luminance or luminance alone. Experiment 2 further explored the link between color and luminance by assessing infants' ability to use pattern differences that included luminance or color to individuate objects. Results indicated that infants individuated objects only when covariations in color and luminance were used. These studies add to a growing body of literature investigating the interaction of color and luminance in object processing in infants and have implications for developmental changes in the nature and content of infants' object representations.

Keywords: object individuation, infants, color, luminance

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Over the last several years, cognitive scientists have shown a great deal of interest in the development of infants' ability to use featural information to individuate objects: to determine whether an object currently in view is the same or a different object than one seen previously (Van de Walle, Carey, & Prevor, 2000; Wilcox, 1999; Woods & Wilcox, 2006; Xu & Carey, 1996). One noteworthy finding is that infants are relatively insensitive to surface features in object individuation tasks until the end of the first year. For example, whereas infants use shape and size information to individuate objects by 4.5 months, they first demonstrate sensitivity to pattern differences at 7.5 months and color or luminance at 11.5 months (Wilcox, 1999; Woods & Wilcox, 2006). This pattern of results has been observed in other object processing tasks, such as object segregation (Needham, 1999) and identification (Tremoulet, Leslie, & Hall, 2001), confirming that there is a developmental hierarchy in the type of featural information infants use to parse and track objects through space and time. A similar pattern is seen in attention to shape and color of artifacts by nonhuman primates (e.g., Santos, Miller, & Hauser, 2003). These results, particularly those relating to color and luminance, are intriguing because infants detect and have memory for color and luminance long before they use these properties to individuate objects (Adams & Maurer, 1984; Aslin, 1987; Bhatt & Rovee-Collier, 1996, 1997; Catherwood, Crassini, & Freiberg, 1987; Oakes, Ross-Sheehy, & Luck, 2006; Peeples & Teller, 1975; Skoczenski, 2002; Slater, Morison, & Rose, 1983; Teller, 1998; Teller, Civan, & Bronson-Castain, 2004). For example, it is clear that by 4.5 months infants perceive colors of all wavelengths and organize color samples into categories similar to adults (e.g., blue, green, red, purple, orange; Bornstein, 1975; Clavadetscher, Brown, Ankrum, & Teller, 1988; Teller, 1998; Teller & Bornstein, 1987; Teller et al., 2004), and infants can detect and remember differences in luminance as small as 9 cd/m^2 (Peeples & Teller, 1975; Teller et al., 2004). Despite infants' ability to detect and remember these properties, they fail to use color or luminance differences as a basis for individuating objects until 11.5 months (Wilcox, 1999). We have argued that one reason infants fail to take into account color or luminance information and instead use shape and size information when individuating objects is that infants are biased to attend to information that is intimately linked to objects, is relatively stable over time, and most accurately predicts how objects move and interact with other objects (Wilcox, 1999; Wilcox & Woods, 2009; Woods & Wilcox, 2006). Thus, when individuating objects, infants are less likely to use color or other surface features because these features may be unreliable.

In previous object individuation studies in which the objects differed only in color or in luminance, infants failed to individuate until 11.5 months (Wilcox, 1999; Woods & Wilcox, 2006). It is possible that immaturities in color and luminance constancies (Chien, Bronson-Castain, Palmer, & Teller, 2006; Chien, Palmer, & Teller, 2003; Dannemiller, 1989; Dannemiller & Hanko, 1987) and infants' uncertainty about how to interpret cast shadows

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(Imura et al., 2006; Van de Walle, Rubenstein, & Spelke, 1998; Yonas & Granrud, 2006), which change as objects or light sources move, lead infants to regard color and lightness as unstable across viewing conditions. This may be particularly true in occlusion events in which objects move in and out of view. Thus, when color or luminance differences are the only indication that two objects are involved in an event, infants fail to take into account this information and instead rely on more dependable information, such as shape or size.

For this reason, we hypothesized that infants might be more likely to attend to color and luminance information in an object individuation task if these two features covaried, thus providing a more reliable indicator of distinct objects. By 7 months, infants have had abundant opportunity to observe covariations of color and luminance in the environment. In natural scenes, the color and luminance of one surface varies reliably from the color and luminance of a different surface (Fine, MacLeod, & Boynton, 2003). This means that color and luminance covariations are highly indicative of discrete surfaces, including objects. Because infants, like adults, are particularly sensitive to regularities found in their environment (Fiser & Aslin, 2001, 2005; Saffran, 2003), it is highly likely that infants come to view covariations of color and luminance as more predictive of the presence of distinct objects than variations of either feature alone. In addition, when luminance cues are ambiguous, color serves to disambiguate luminance information, given that color variations rarely occur in conjunction with shadows but frequently occur in conjunction with changes in object surfaces (Kingdom, 2003; Kingdom, Beauce, & Hunter, 2004; Kingdom, Rangwal, & Hammamji, 2005). Thus, although neither property alone is sufficient to individuate objects, together they may be considered a dependable source of information for tracking the identity of objects through occlusion.

The Present Research

The present experiments were designed to assess the extent to which infants' capacity to individuate objects would be enhanced if color differences co-occurred with luminance differences. Two experiments were conducted to test 7-month-olds' ability to individuate objects on the basis of color differences, luminance differences, or both, using solid-colored and patterned objects. We expected that infants would individuate objects at an earlier age when color and luminance covaried than when only color or luminance differed, regardless of whether the objects themselves differed in color and luminance (Experiment 1) or the pattern on the objects was created using color and luminance contrast (Experiment 2). In each case, covariations of color and luminance provide a more salient and reliable source of information than either color or luminance alone.

Experiment 1

Experiment 1 assessed 7.5-month-olds' ability to individuate objects that differ in both color and luminance, using the narrow-screen task of Wilcox and Baillargeon (1998a, 1998b).[1] Infants were tested in one of two conditions: green–red and orange–purple. In the green–red condition, infants saw the green ball and red ball emerge successively to either side of a screen that was either too narrow (narrow-screen event) or sufficiently wide (wide-screen event) to simultaneously hide both balls (see Figure 1). In the orange–purple condition, the two balls were orange and purple, respectively.[2] In each condition, the balls differed in both color and luminance. If 7.5-month-olds use color and luminance differences to specify the presence of distinct objects and correctly infer that both objects can be fully occluded by the wide but not the narrow screen, then they should find the narrow- but not the wide-screen event unexpected (i.e., infants should look longer at the narrow- than the wide-screen test event). Conversely, if infants fail to use these features to individuate the objects, they should look equally at the narrow- and wide-screen test events.

Method

Participants. Participants were thirty-six 7.5-month-olds (M = 7 months, 15 days). A priori power analyses indicated that 36 infants were sufficient to obtain power greater than 0.80 at an effect size equal to 0.80. In this and the following experiments, participants were recruited using birth announcements and commercialized lists from a midsize college town and surrounding areas in the south-central region of the U.S. They were from predominantly middle-class families whose parents reported having had at least some college education. Parents reported their infant's race or ethnicity as Caucasian (N = 30), Hispanic (N = 2), Black (N = 1), or of mixed race (N = 3). Eight additional infants were tested but removed from analysis due to fussiness (N = 3), inability of the primary observer to determine direction of gaze (N = 3), or procedural problems (N = 2). Nine infants (four male, five female) were pseudorandomly assigned to one of four groups formed by crossing color pair (green–red or orange–purple) with screen size (narrow or wide). Parents were contacted by letters and follow-up phone calls.

Apparatus and stimuli. To ensure that results were comparable to previous studies, we constructed the display environment to be identical to our previous investigations of infants' use of color and luminance (Wilcox, 1999; Woods & Wilcox, 2006). The apparatus consisted of a wooden cubicle 213 cm high, 105 cm wide, and 43.5 cm deep. The floor and walls were cream colored or covered with low-contrast patterned contact paper. A muslin shade was lowered over an opening in the front wall of the apparatus at the end of each trial. A platform 1.5 cm tall, 60 cm wide, and 19 cm deep sat at the back wall, centered between the side walls. Two muslin-covered frames, 214 cm high and 68 cm wide, stood at an angle to either side of the apparatus concealing two observers and isolating infants from the experiment room. In addition to room lighting, a 20-W fluorescent bulb was affixed inside each of the apparatus walls.

The balls used in the familiarization and test events were Styrofoam, 10.25 cm in diameter. The balls were painted using

[1] For a review of evidence that the narrow-screen task is a reliable measure of object individuation in infancy see Wilcox et al. (2002) and Wilcox & Woods (2009).

[2] Previous studies indicate that infants do not individuate objects on the basis of green–red (Wilcox, 1999, Experiment 4A) or orange–purple (Woods, 2006, Experiment 1, additional results) color differences in the absence of luminance differences. The luminance values of the objects in Wilcox (1999; Experiment 4A), which were not reported, were each 55 cd/m^2.

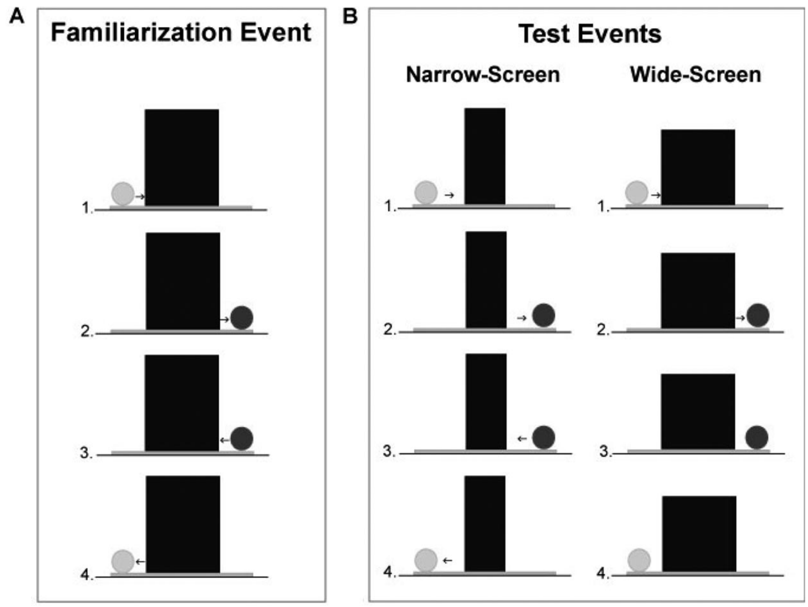

Figure 1. Schematic drawing of the green–red familiarization and test events seen in Experiment 1. Infants first saw the familiarization event (A). After the familiarization event, infants saw either a narrow- or a wide-screen test event (B). The orange–purple condition of Experiment 1 and the luminance contrast and color contrast conditions of Experiment 2 were identical to those in the green–red condition except that the green and red balls were replaced with the balls appropriate for each condition.

nontoxic acrylic paints. CIELAB 1976 color measurements were obtained using an X-Rite SP64 spectrophotometer under an F2 standard illuminant and 10° standard observer. Specular reflectance included (SPIN) mode was selected during measurement to account for subtle glare on the objects' surfaces. Three points on each object were sampled and resulting measurements were averaged. These measurements are as follows: green ball, $L^* = 68.79$, $a^* = -14.56$, $b^* = 7.39$; red ball, $L^* = 40.12$, $a^* = 32.76$, $b^* = 18.69$; orange ball, $L^* = 65.28$, $a^* = 34.08$, $b^* = 59.19$; purple ball, $L^* = 28.55$, $a^* = 7.43$, $b^* = -7.08$. Measurements of overall difference in color space (i.e., ΔE^*_{ab}) for each object pair are displayed in Table 1. Recall that infants are capable of detecting and remembering differences across color categories and across luminance differences as small as 9 cd/m^2. These color and luminance differences (i.e., green–red, $\Delta L^* = 28.67$, and orange–purple, $\Delta L^* = 36.73$) are well within infants' discrimination and memory abilities (Bhatt & Rovee-Collier, 1996, 1997; Catherwood et al., 1987; Peeples & Teller, 1975; Teller, 1998; Teller et al., 2004; color photographs of the apparatus and stimuli used in this study can be viewed in the supplemental materials). Two color pairs and two luminance differences were used to ensure that results were not confined to a single color or luminance difference. Each ball was mounted on a clear Plexiglas base with a handle 16 cm long that protruded through an opening 3.25 cm high between the back wall and floor of the apparatus; the opening was masked by cream-colored fringe. Using the Plexiglas handle, an experimenter concealed behind the apparatus moved the balls along the platform.

Embedded in the center of the platform was a metal bilevel shelf with an upper and lower level 16 cm apart; each shelf was 12.7 cm wide and 13 cm deep. The bilevel shelf was lifted and lowered by means of a handle protruding through an opening in the apparatus's back wall, allowing the balls to emerge successively from behind the screen.

The familiarization screen consisted of yellow matte board (30 × 41 cm). The narrow (15.5 × 41 cm) and wide (30 × 33 cm) test screens were made from dark blue matte board decorated with small gold stars. The screens were mounted on a wooden stand centered in front of the platform.

Procedure. Each infant participated in a two-phase procedure consisting of a familiarization and test phase. The infant sat on a

Table 1
Overall Difference Between Stimuli in Three-Dimensional Color Space

Object pair	Feature variation	ΔE^*_{ab}
Green–red	Color & luminance	56.47
	Color[a]	57.83
Light green–green	Luminance	29.66
Orange–purple	Color & luminance	80.32
	Color[b]	91.40
Light purple–purple	Luminance	39.22
Gray–black	Luminance[c]	36.19
White–black	Luminance	65.93

Note. Total differences in color space are accounted for by ΔE values. These values are calculated using difference measurements between each pair of stimuli in hue (i.e., red–green = Δa; blue–yellow = Δb) and luminance (i.e., ΔL).
[a] For comparison, color measurements were taken from stimuli used by Wilcox (1999; Experiment 4A). [b] Color measurements were taken from stimuli used by Woods (2006; Experiment 1, additional results). [c] Color measurements were taken from stimuli used by Woods and Wilcox (2006).

parent's lap approximately 80 cm from the objects on the platform (see Figure 2). Objects subtended an angle of 7.3°. During the familiarization phase, infants saw the familiarization event appropriate for their condition on six successive trials. At the start of each familiarization trial, the green ball sat at the left end of the platform. The red ball rested on the lower level of the bilevel hidden behind the screen. After the infant looked at the green ball for 1 s, the ball paused (1 s) and moved behind the right edge of the screen (2 s); after a brief interval (1 s) the red ball emerged from behind the screen and moved to the right until it reached the end of the platform (2 s). The ball then reversed its trajectory and the event just described was seen in reverse. The entire 12-s event sequence was then repeated continuously until the trial ended. Each trial terminated when the infant (a) looked away for 2 consecutive seconds after having looked at the event for at least 12 cumulative seconds or (b) looked for 60 cumulative seconds without looking away for 2 consecutive seconds.

During the test phase, the infants saw the test event appropriate for their condition on four successive trials. The test events were identical to the familiarization event except that the familiarization screen was replaced by the narrow or wide test screen. Trial termination criteria were the same except that minimum looking time was 6 s (rather than 12 s). Two observers monitored infants' looking behavior online through peepholes in the frames to either side of the apparatus. Each observer held a game pad connected to a Dell computer and depressed a button when the infant attended to the event. Interobserver agreement for this and the following experiment averaged 93%.

Results

Familiarization trials. The infants' looking times during the six familiarization trials (see Figure 3) were averaged and compared by means of a 2 × 2 analysis of variance (ANOVA), with color (green–red or orange–purple) and screen (narrow or wide) as between-subjects factors. The probability of a Type I error was maintained at .05 for this and subsequent analyses unless otherwise specified. The main effects of color, $F(1, 32) = 0.02$, and screen, $F(1, 32) = 0.10$, were not significant, nor was their interaction, $F(1, 32) = 2.15$, indicating that infants in the four conditions did not differ reliably in their mean looking times during familiarization trials (green–red narrow-screen, $M = 32.86$, $SD = 5.21$; green–red wide-screen, $M = 37.33$, $SD = 4.63$; orange–purple narrow-screen, $M = 36.92$, $SD = 9.07$; orange–purple wide-screen, $M = 34.00$, $SD = 9.90$).

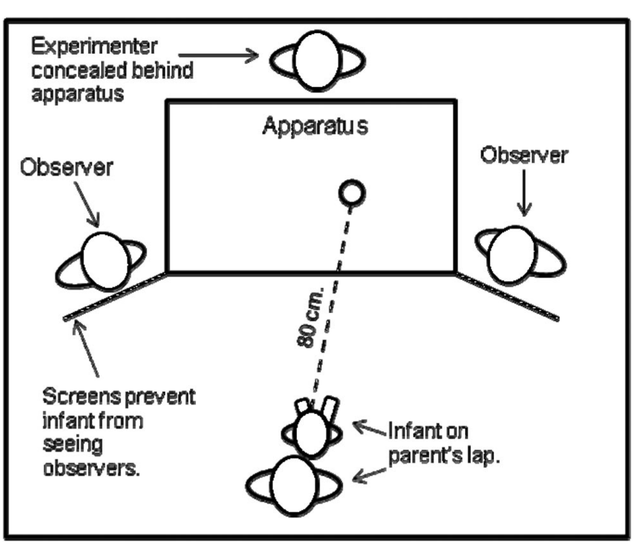

Figure 2. Bird's-eye view of the testing situation.

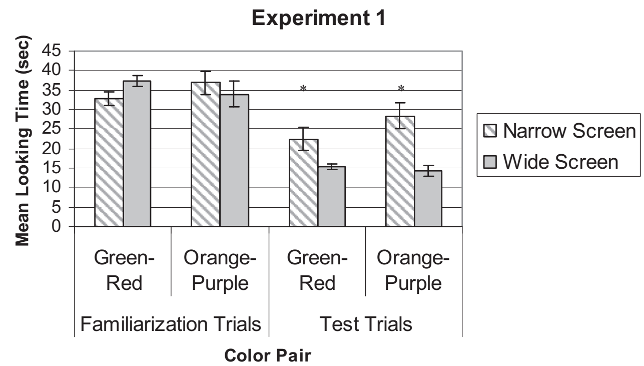

Figure 3. Mean looking times (in seconds, with standard error bars) of the 7.5-month-olds in Experiment 1 during the familiarization and test trials. Asterisks represent significance at $\alpha \leq .05$.

Test trials. Infants' looking times during the four test trials (see Figure 3) were averaged and analyzed in the same manner as the familiarization trials. The main effect of color, $F(1, 32) = 1.12$, and the Color × Screen interaction, $F(1, 32) = 2.16$, were not significant. However, the main effect of screen was significant, $F(1, 32) = 20.03$, $p < .001$, $\eta_p^2 = 0.39$. Planned comparisons indicated that this result held for the green–red pair (narrow-screen, $M = 22.48$, $SD = 8.93$; and wide-screen, $M = 15.43$, $SD = 2.19$), $t(32) = 2.13$, $p = .04$, Cohen's $d = 1.08$, and orange–purple pair (narrow-screen, $M = 28.43$, $SD = 9.88$, and wide-screen, $M = 14.46$, $SD = 4.06$), $t(32) = 4.20$, $p < .001$, Cohen's $d = 1.85$.[3] Mann-Whitney nonparametric analyses indicated significant differences in looking to the narrow- versus wide-screen events for infants who saw the green–red color pair, $U = 16.00$, $p = .02$ (one-tailed), Cohen's $d = 1.2$, and the orange–purple color pair, $U = 7.00$, $p = .001$ (one-tailed), Cohen's $d = 2.0$, $\alpha = .025$.

Additional results. One explanation for these results is that because two features rather than one varied, the overall difference between the objects was increased when compared to objects that varied in color alone or in luminance alone. One way to investigate this possibility is to examine delta E (ΔE^*_{ab}) values. These values account for differences in luminance and color and therefore provide a numerical value of the total difference between any two sets of stimuli in color space (Commission Internationale de L'Eclairage, 2004). These values are displayed in Table 1. If infants individuated objects when both color and luminance varied as a result of an increase in the overall difference between the objects, we would expect overall difference scores (i.e., ΔE values)

[3] Data in this and subsequent analyses were subjected to a square root transformation to accommodate slight (although not significant) skew in the data. Transformation did not significantly alter the results.

for the green–red and orange–purple objects that differed in both color and luminance to be much higher than those of the green–red and orange–purple objects that differed in color alone. Examination of delta E values reveals, however, that this pattern was not found for either object pair. The overall difference value for the green and red balls that varied in color alone (i.e., those used in Wilcox, 1999, Experiment 4A) and in color and luminance (i.e., those used in the current study) were nearly identical (color alone, $\Delta E^*_{ab} = 57.83$; color and luminance, $\Delta E^*_{ab} = 56.47$). Furthermore, the orange and purple ball pairs' ΔE values were in the opposite direction from what we expected. The color-alone pair had a value of $\Delta E^*_{ab} = 91.40$; contrary to expectations, the color and luminance pair had a much lower value of $\Delta E^*_{ab} = 80.32$. These values support our hypothesis that infants' ability to individuate objects is due to factors other than the magnitude of the difference between objects in the feature space. That is, when infants individuated the objects that varied in both color and luminance, whether green to red or orange to purple, their ability to use these features as a basis for object individuation was not enhanced due to an increase in the overall difference between the objects.

Another way to test the hypothesis that the magnitude of the difference between objects is the determining factor leading to successful object individuation is to increase the difference between objects along a single feature dimension. Therefore, an additional sixteen 7.5-month-old infants ($M = 7$ months, 15 days; Caucasian, $N = 15$, Hispanic, $N = 1$) were tested in an event in which objects differed in luminance alone, but the difference values exceeded those of the green and red different-luminance balls used in Experiment 1. The procedure was identical to that used in Experiment 1 except that infants saw a white ball ($L^* = 93.11$, $a^* = -0.19$, $b^* = 1.72$) to the left side of the occluder and a black ball ($L^* = 27.23$, $a^* = 0.26$, $b^* = -0.75$) to the right side. Looking times during familiarization trials (see Figure 4) were analyzed by means of an independent-samples t test. Results indicated no significant differences between narrow-screen ($M = 36.74$, $SD = 9.64$) and wide-screen ($M = 38.22$, $SD = 7.62$) conditions, $t(14) = -0.34$, $p = .74$. Mean looking times during test (see Figure 4) trials were analyzed in the same manner as familiarization trials and results revealed no significant differences between narrow-screen ($M = 26.48$, $SD = 9.37$) and wide-screen ($M = 22.88$, $SD = 9.82$) test events, $t(14) = .75$, $p = .47$, Cohen's $d = 0.38$. Mann-Whitney nonparametric analyses supported these results, $U = 24.00$, $p = .40$. These results suggest that even when

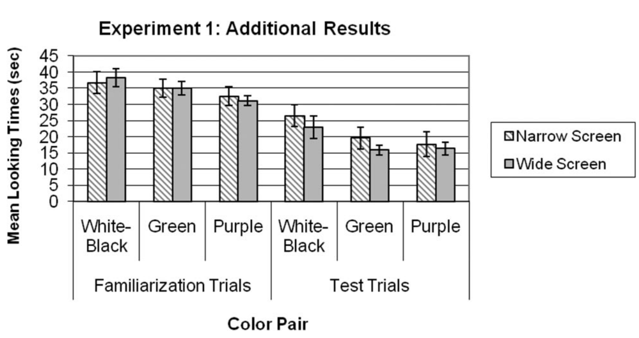

Figure 4. Mean looking times (in seconds, with *SE* bars) of the 7.5-month-olds in Experiment 1, additional results during the familiarization and test trials.

objects' luminance differences were exceedingly high ($\Delta L^* = 65.88$) and overall difference measurements exceeded those of the green–red color and luminance object pair from Experiment 1 that infants used as a basis for object individuation (i.e., white–black pair, $\Delta E^*_{ab} = 65.93$; green–red pair, $\Delta E^*_{ab} = 56.41$), infants did not use this luminance difference alone to individuate the objects. These results provide additional evidence to support the idea that it is not simply the magnitude of the difference between the objects in the feature space that determines infants' use of these features.

Finally, given the intricate link between color and luminance processing (Farell, 1999; Kingdom et al., 2005; Takeuchi, De Valois, & Hardy, 2003), it is necessary to ensure that the results from Experiment 1 were not obtained because viewing luminance differences on chromatic objects is simply more salient than luminance differences on achromatic objects. To investigate this possibility, we tested an additional thirty-six 7.5-month-olds ($M = 7$ months, 18 days; Caucasian, $N = 25$, Hispanic, $N = 7$, Asian, $N = 2$, mixed race, $N = 2$) using the same procedure as Experiment 1 except that the chromatic objects differed only in luminance. Infants saw one pair of green balls or purple balls. The green ball from Experiment 1 was paired with a darker green ball approximating the luminance of the red ball from Experiment 1. Conversely, the dark purple ball from Experiment 1 was paired with a lighter purple ball that approximated the luminance of the orange ball from Experiment 1. Color measurements were assessed as in Experiment 1 and were as follows: green $L^* = 68.79$, $a^* = -14.56$, $b^* = 7.39$ and $L^* = 44.09$, $a^* = -24.92$, $b^* = 20.15$; purple $L^* = 60.60$, $a^* = 11.61$, $b^* = -29.28$ and $L^* = 28.55$, $a^* = 7.43$, $b^* = -7.08$. The luminance difference for the green pair was $\Delta L^* = 24.7$; for the purple pair it was $\Delta L^* = 32.05$. The ball with the highest luminance measure (lightest) was seen to the left of the screen and the ball with the lowest (darkest) was seen to the right of the screen. Looking times during familiarization trials (see Figure 4) were averaged and compared by means of a 2×2 ANOVA, with color (green or purple) and screen (narrow or wide) as between-subjects factors. The main effects of color, $F(1, 32) = 1.61$, and screen $F(1, 32) = 0.12$, were not significant nor was the Color $\times$ Screen interaction, $F(1, 32) = 0.11$ (green narrow-screen, $M = 34.99$, $SD = 8.55$; green wide-screen, $M = 34.95$, $SD = 6.40$; purple narrow-screen, $M = 32.71$, $SD = 8.70$; purple wide-screen, $M = 31.09$, $SD = 4.63$).

Looking times in test (see Figure 4) were analyzed in the same manner as familiarization trials. The main effect of neither color pair, $F(1, 32) = 0.09$, nor screen, $F(1, 32) = 0.93$, were significant, nor was the interaction between color pair and screen, $F(1, 32) = 0.23$, indicating that for each color pair, infants' looking times to the narrow- and the wide-screen events did not reliably differ (green narrow-screen, $M = 19.64$, $SD = 10.10$; green wide-screen, $M = 15.95$, $SD = 4.44$; purple narrow-screen, $M = 17.64$, $SD = 8.94$; purple wide-screen, $M = 16.40$, $SD = 5.93$). Mann-Whitney nonparametric analyses supported these results for the green color pair, $U = 34.00$, $p = .30$ (one-tailed), Cohen's $d = 0.30$, and the purple color pair, $U = 40.00$, $p = .50$ (one-tailed), Cohen's $d = 0.00$. Although there was a trend for the infants to look longer at the narrow- than the wide-screen test event, the effect size for screen was exceedingly small, $\eta^2_p = .03$, notably smaller than that of Experiment 1, $\eta^2_p = .39$.

To further compare the effect of color plus luminance differences to luminance changes alone, we compared looking times by means of a 2 × 2 ANOVA, with experiment (color plus luminance difference or luminance difference alone) and screen (narrow or wide) as between-subjects factors. The main effect of experiment, $F(1, 68) = 2.81$ was not significant. The main effect of screen was significant, $F(1, 68) = 12.98$, $p = .001$, $\eta_p^2 = .16$, as was the Experiment × Screen interaction, $F(1, 68) = 5.61$, $p = .02$, $\eta_p^2 = .08$. Planned comparisons indicated that infants looked significantly longer at the narrow- than the wide-screen event when color plus luminance differences were used, $t(68) = 4.30$, $p < .001$, Cohen's $d = 1.46$ (color + luminance, narrow screen, $M = 25.46$, $SD = 9.63$; color + luminance, wide screen, $M = 14.95$, $SD = 3.30$). In contrast, infants who saw only a luminance difference looked equally to the narrow and wide screens, $t(68) = 1.01$, $p = .32$, Cohen's $d = 0.33$ (luminance differences alone, narrow screen, $M = 18.64$, $SD = 9.31$; luminance differences alone, wide screen, $M = 16.18$, $SD = 5.09$). Thus, the infants who saw objects that were chromatic but differed only in luminance failed to individuate the objects. These results suggest that viewing luminance differences alone does not support object individuation in 7.5-month-olds, regardless of whether the objects are chromatic or achromatic.

Discussion

The outcome of Experiment 1 suggests that infants used color and luminance differences combined to individuate the objects. These results contrast with those obtained in studies in which color alone (Wilcox, 1999) or luminance alone (Woods & Wilcox, 2006) were used and suggest that covariations in color and luminance together are a more reliable or salient source of information than either color or luminance alone. Furthermore, additional analyses and examination of ΔE values suggest these results were not due to an increase in the difference between stimuli in the feature space when color and luminance were covaried nor to increased salience of luminance differences on colored (in contrast to achromatic) stimuli.

These findings raise the question of whether the advantage of viewing covariations in color and luminance is specific to objects that are simple in their composition, like the objects used in Experiment 1 (i.e., each ball was a single color and luminance, and the two balls differed only on these dimensions) or whether this advantage would be seen with more complex objects. Most objects in the natural environment posses a variety of colors and vary on their surface pattern. Would infants attend to covariations of color and pattern within this context of surface pattern and use these differences as the basis for tracking the identity of objects?

We suspect that the answer to this question is positive, for several reasons. First, when patterns are created using both color and luminance, they are more reliable than patterns created using luminance-only or color-only variations. For example, when created by luminance cues alone, patterns are ambiguous because they may signify variations in illumination (e.g., shadows), rather than variations in the surface attributes of the object. In addition, color changes that occur when infants see colored objects under diverse lighting conditions[4] may render patterns created by variations in color alone unreliable. However when these features covary, the likelihood that the pattern seen on the surface of each object is a result of lighting conditions is reduced, perhaps leading infants to view the patterns as a feature inherent to the object itself and thereby a reliable indicator of distinct objects.

Another advantage of studying pattern is that because patterns are created using variations in color and luminance, these two features can be manipulated without changing the pattern, itself. Thus, the question we ask is, if two objects differ only in pattern, will infants use this difference to individuate objects when the pattern is made from color alone, luminance alone, or color and luminance together? If, for example, infants use pattern differences that are created from color and luminance but fail to use pattern differences that are created from color alone, this result would demonstrate that the objects themselves need not always vary with respect to two feature dimensions. This result would also indicate that infants perform differently with higher order differences (i.e., pattern) created using two feature dimensions (e.g., color and luminance) than with those same differences created using a single feature dimension (e.g., colored patterns).

Experiment 2

Experiment 2 assessed 7.5-month-olds' ability to use pattern differences to individuate objects when the surface pattern was created with a color or a luminance contrast. Wilcox (1999) demonstrated that 7.5-month-olds successfully individuate objects on the basis of a pattern difference (i.e., a dotted ball and a striped ball). The dotted and striped patterns were created using areas contrasting in both color and luminance, and the color and luminance contrasts used were identical for each ball. We hypothesized that if the patterns had been created using only color differences (i.e., the dots or stripes varied only in color) or only luminance differences (i.e., the dots or stripes varied only in luminance), the infants would have failed to individuate based on pattern information.

Method

Participants. Participants were thirty-six 7.5-month-olds ($M = 7$ months, 16 days). Parents reported their infant's race or ethnicity as Caucasian ($N = 28$), Hispanic ($N = 3$), Black ($N = 2$), Asian ($N = 1$), or of mixed race ($N = 2$). One additional infant was tested but removed from analysis due to fussiness. Infants were pseudorandomly assigned to one of the four experimental groups formed by crossing pattern (luminance or color contrast) with screen size (narrow or wide).

Apparatus, stimuli, and procedure. The apparatus, stimuli, and procedure of Experiment 2 were identical to that of Experiment 1, except that one pair of balls was achromatic dotted and striped and the other pair was chromatic isoluminant dotted and striped (see Figure 5). The dotted ball was seen to the left at the beginning of each trial. The balls were identical to the dotted and

[4] Different light sources have diverse spectral compositions (CIE, 2004). As a result, viewing a colored pattern under two different light sources changes the color of the pattern (seen as reflectance). Generally, color constancy in adults accommodates changes in lighting, so that the colors appear consistent under a variety of lighting conditions. In infants, however, color constancy is immature (Dannemiller, 1989; Dannemiller & Hanko, 1987), so a patterned object seen under two different light sources may appear to have patterns of entirely different colors.

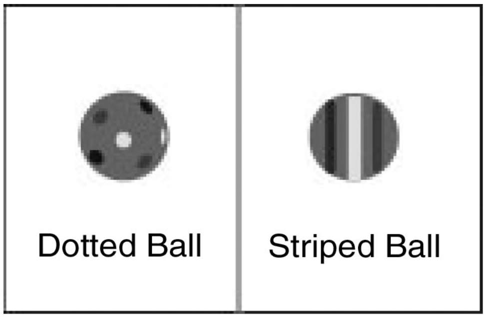

Figure 5. Rendering of the dotted and striped balls used in Experiment 2 and in Wilcox (1999), Experiment 3A. In Experiment 2, patterns were created by color alone (color-contrast condition) or luminance alone (luminance-contrast condition), whereas in Wilcox (1999), patterns were created using both color and luminance contrast. Color photographs are available in the supplemental materials to this article.

striped balls of Wilcox, 1999 (Experiment 3A), with the exception of the paints used. The achromatic dotted ball was grey (55 cd/m^2) with dots, 2.5 cm in diameter, that varied in luminance (111 cd/m^2, 45 cd/m^2, and 59 cd/m^2; see Figure 5). The achromatic striped ball was identical to the dotted ball except that the dots were replaced with 1.3-cm-wide stripes spaced approximately 2 cm apart. The chromatic dotted and striped balls were painted green with a uniform luminance of 55 cd/m^2 and covered with dots (or stripes) that varied only in color (i.e., yellow, blue, and red). Previous research indicated that patterns from these luminance and color variations are well within infants' detection and memory capacities (Bhatt & Rovee-Collier, 1996, 1997; Catherwood et al., 1987; Peeples & Teller, 1975; Teller, 1998; Teller et al., 2004); accordingly, regardless of how the pattern is created, infants should be able to both detect and remember the patterns.

Results and Discussion

Familiarization trials. Infants' looking times during familiarization trials (see Figure 6) were averaged and compared by means of a 2 × 2 ANOVA, with pattern (luminance contrast vs. color contrast) and screen (narrow vs. wide) as between-subjects factors. The main effects of pattern and screen were not significant, nor was the interaction between pattern and screen, $Fs(1, 32) < 1$, indicating that infants in the four different conditions did not differ reliably in their mean looking times during familiarization trials (luminance contrast narrow screen, $M = 35.19$, $SD = 5.71$; luminance contrast wide screen, $M = 35.89$, $SD = 8.65$; color contrast narrow screen, $M = 33.19$, $SD = 8.19$; color contrast wide screen, $M = 35.52$, $SD = 7.42$).

Test trials. Infants' mean looking times during the four test trials (see Figure 6) were averaged and analyzed in the same manner as the familiarization trials. The main effects of pattern and screen were not significant, nor was the interaction between pattern and screen, $Fs(1, 32) < 1$, indicating that for each pattern type, infants looked equally at the narrow- and the wide-screen test events (luminance contrast narrow screen, $M = 15.38$, $SD = 3.16$; luminance contrast wide screen, $M = 15.12$, $SD = 3.80$; color contrast narrow screen, $M = 14.84$, $SD = 6.85$; color contrast wide screen, $M = 12.27$, $SD = 3.17$). When the objects differed in patterns created using a luminance contrast (color remained constant) or a color contrast (luminance remained constant), infants failed to individuate the objects, thus supporting the conclusion that 7.5-month-olds use these pattern differences to individuate objects only when the pattern is created using areas contrasting both in color and in luminance. These results demonstrate that the extent to which these pattern differences are used depends, at least in part, on whether pattern was created by color contrast, luminance contrast, or both and that infants can successfully individuate objects on the basis of one feature dimension as long as that feature dimension is sufficiently salient.

Additional analyses. To directly test our hypothesis, we conducted additional analyses to compare the results obtained in Experiment 2 with the results obtained by Wilcox (1999, Experiment 3B), in which patterns were created using both color and luminance contrasts. Participants were twelve 7.5-month-olds ($M = 7$ months, 19 days). The events were identical to the color-contrast and luminance-contrast, narrow- and wide-screen events seen in Experiment 2, with one exception: The dotted and striped patterns were created using areas contrasting in both color and luminance. The color and luminance contrasts that gave rise to the patterns were identical in color to those of the color-contrast patterns (i.e., yellow, blue, and red dots or stripes) and identical in luminance to those of the luminance-contrast patterns (i.e., dots or stripes of 111 cd/m^2, 45 cd/m^2, and 59 cd/m^2) of Experiment 2.

Looking times during the familiarization trials were averaged and analyzed by means of a 3 × 2 ANOVA with pattern (color contrast, luminance contrast, or color and luminance contrast) and screen (narrow or wide) as the between-subjects factors. The main effects of pattern and screen, $Fs(1, 42) < 1$, were not significant, nor was the Pattern × Screen interaction, $F(1, 42) = 1.13$, indicating that the infants in the six different conditions did not differ reliably in their mean looking times during the familiarization trials (color and luminance contrast, narrow screen, $M = 37.15$, $SD = 9.89$; color and luminance contrast, wide screen, $M = 31.02$, $SD = 7.03$; luminance contrast, narrow screen, $M = 35.19$, $SD = 5.71$; luminance contrast, wide screen, $M = 35.89$, $SD = 8.65$; color contrast, narrow screen, $M = 33.19$, $SD = 8.19$; color contrast, wide screen, $M = 35.52$, $SD = 7.42$).

Looking times during the test trials were analyzed in the same manner as familiarization trials. The main effects of pattern, $F(1, 42) = 13.54$, $p < .001$, $\eta_p^2 = .39$, and screen, $F(1, 42) = 9.90$, $p =$

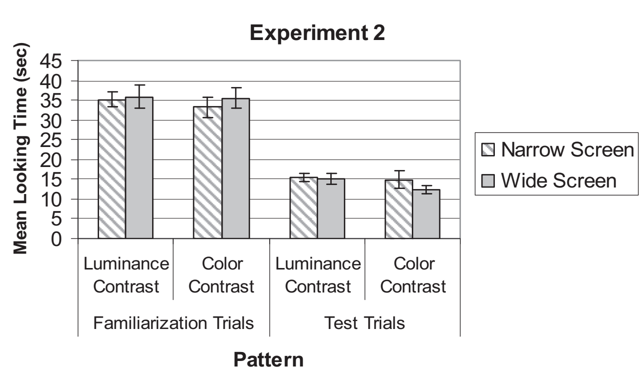

Figure 6. Mean looking times (with standard error bars) of the 7.5-month-olds in Experiment 2 during the familiarization and test trials.

.003, η_p^2 = .19, were significant, as was the Pattern × Screen interaction, $F(1, 42) = 4.38$, $p = .02$, $\eta_p^2 = .17$. These results suggest that the infants in the three pattern conditions responded differently to the test events. Planned comparisons indicated that when pattern was created using both color and luminance contrasts, infants looked reliably longer at the narrow-screen (M = 28.27, SD = 5.73) than at the wide-screen test event (M = 17.47, SD = 6.51), $t(42) = 3.82$, $p < .001$, Cohen's d = 1.78. In contrast, when pattern was created using luminance contrast only, infants looking to the narrow-screen (M = 15.38, SD = 3.16) and wide-screen events (M = 15.12, SD = 3.80) did not reliably differ, $t(42) = 0.11$, $p = .91$. Nor did they reliably differ when pattern was created using color contrast alone, $t(42) = 1.10$, $p = .28$ (color contrast, narrow screen, M = 14.84, SD = 6.85; color contrast, wide screen, M = 12.27, SD = 3.17). Planned comparisons also indicated that infants looked reliably longer at the narrow-screen event when pattern was created using both color and luminance contrasts (M = 28.27, SD = 5.73) than when pattern was created from luminance differences alone (M = 15.38, SD = 3.16), $t(42) = 4.94$, $p < .001$, Cohen's d = 2.97, or color differences alone (M = 14.84, SD = 6.85), $t(42) = 5.15$, $p < .001$, Cohen's d = 2.08. These results provide converging evidence for the conclusion that 7.5-month-olds use pattern differences to individuate objects only when the pattern is created using areas contrasting in both color and luminance.

Conclusion

Two experiments were conducted to assess infants' sensitivity to color and luminance information during an object individuation task. In each experiment, 7.5-month-old infants saw an individuation event in which the objects seen to either side of an occluder differed from one another along one or two feature dimensions. In the first experiment, the two objects differed in both color and luminance (i.e., two features were varied). In the second experiment, the objects differed only in pattern (i.e., a single feature was varied), and the pattern (dotted or striped) was created using either color alone (luminance was constant) or luminance alone (color remained constant). Looking times revealed that infants are more sensitive to color and luminance information when these sources of information simultaneously vary than when one varies independently of the other. This held true both for differences between objects (Experiment 1), and for patterns seen on objects' surfaces (Experiment 2). Additional analyses suggest these results were not due to an increase in the magnitude of the difference between the two objects.

Why might infants be more likely to individuate objects when both color and luminance information are used? One possibility is that infants use color and luminance combinations because together these features are more reliable. We have argued that one reason infants fail to use color and luminance differences to individuate objects until the end of the first year is because infants do not regard these features as being intimately linked to objects and view color and luminance information as less stable over time and viewing conditions than other features (Wilcox, 1999; Wilcox, Schweinle, & Chapa, 2003; Woods & Wilcox, 2006). Consequently, these features are an unreliable source of information and cannot be depended on as a basis for object individuation. As we have discussed in previous sections, this hypothesis is, in part, based on infants' immaturities in lightness and color constancies (Chien et al., 2006; Chien et al., 2003; Dannemiller, 1989; Dannemiller & Hanko, 1987) and inability to correctly interpret cast shadows (Imura et al., 2006; Van de Walle et al., 1998; Yonas & Granrud, 2006). As a result, infants are less likely to attend to and rely on changes in color or lightness when interpreting occlusion events.

When however, both color and luminance vary, infants may consider this type of change sufficiently reliable to support object individuation. It is possible that infants recognize early in development that color or luminance differences alone can be ambiguous and that covariations disambiguate surface information in a way that is sufficiently reliable to use as a basis for object individuation. When two objects differ in both color and luminance (Experiment 1), together these features provide a dependable source of information to indicate the presence of distinct objects. When patterns composed of both color and luminance are used (Experiment 2), the pattern is sufficiently reliable to be used for tracking the identity of objects through occlusion events. In sum, object properties that infants perceive as inconsistent or arbitrary are considered an insufficient source of information for object individuation, but if those properties are perceived as more reliable when seen together, infants will attend to them.

One question this hypothesis raises is whether these results are specific to color and luminance or if infants will be more likely to individuate objects when any two features covary, regardless of which two features are used. Presumably, when objects vary along more than a single feature dimension, the probability that the objects are distinct is increased. We predict, however, that regardless of the number of features that indicate distinct objects, infants will only individuate the objects if these features are considered dependable. If the features are not reliable indicators of distinct objects and if covarying the features does not increase the likelihood that they are reliable, infants will fail to use them as a basis for object individuation. Additional studies to address this issue and related questions, such as when and how infants come to determine which features are reliable, are currently underway.

Another explanation for the current results is that varying two features, rather than one, increases the likelihood that infants will individuate objects due to an increase in lower level perceptual information. However, examination of overall differences between objects in the feature space and additional results indicate that even when differences along a single feature dimension (i.e., luminance) are high, infants still fail to individuate objects; this provides evidence that perceptual saliency cannot fully account for the effects reported here.

Finally, it is possible that both perceptual and cognitive mechanisms work together to improve performance (Gegenfurtner & Rieger, 2000). One way to test the contribution of these two factors is to make the feature differences equally salient to infants. Kaldy, Blaser, and Leslie (2006), have developed a procedure to equate the salience of object features using a modified version of the forced-choice preferential looking method (Teller, 1979). Using this method, it may be possible to construct stimuli that differ in color, luminance, and both color and luminance, yet are identical in perceptual salience.

These findings are the first evidence that color and luminance differences, when combined, facilitate object individuation in the infant even when color and luminance alone do not support the individuation process. These data provide converging evidence for the hypothesis that infants' capacity to use surface features within the context of an object individuation task is not either/or but instead depends on the nature of the task and the reliability of the information available to the infant (Wilcox & Baillargeon, 1998a; Wilcox & Chapa, 2004; Wilcox, Woods, & Chapa, 2008; Wilcox, Woods, Chapa, & McCurry, 2007). These data also highlight the complexity of using color and luminance information to interpret physical events and has implications for our understanding of object cognition, more generally.

For instance, we suspect that other cognitive tasks in which infants have failed to show sensitivity to color information such as object segregation (Needham, 1999) or categorization (Catherwood, Crassini, & Freiberg, 1989) may similarly benefit by pairing luminance and color differences. Although previous studies have investigated infants' ability to use color both to segregate and to categorize objects (Catherwood et al., 1989; McMurray & Aslin, 2004; Needham, 1999), no studies have purposefully examined the contribution of both color and luminance to these abilities. It is important to note, however, that we believe the reason infants fail to attend to these features when individuating objects is that these features are unreliable as indicators of distinct objects. Accordingly, it is possible that covarying these two features will only facilitate performance in cognitive tasks in which object distinction is important (e.g., object segregation).

These findings may also provide an explanation for inconsistencies in color research found within the infancy literature. Numerous studies have examined the effect of color variations on infants' performance on object processing tasks without also taking into account variations in luminance (e.g., Bhatt & Rovee-Collier, 1997; Bushnell & Roder, 1985; Mash, 2007; McMurray & Aslin, 2004; Needham, 1999; Oakes et al., 2006; Saylor & Ganea, 2007; Tremoulet et al., 2001). In light of the current findings, it is possible that what appear to be inconsistencies in the age at which infants use color when reasoning about objects are actually differences in the presence of luminance variations (i.e., variations in color and luminance compared to variations in color alone). For example, we have found that infants younger than 11 months are relatively insensitive to color differences alone for individuating objects (Wilcox, 1999; Wilcox et al., 2007), but other studies on infants' abilities to reason about objects on the basis of color indicate that infants are sensitive to color earlier in other tasks (e.g., Mash, 2007; Needham & Ormsbee, 2003; Oakes et al., 2006). For example, Oakes et al. (2006) found that by 7.5 months infants store both the color and location of an object in short term memory. With the ability to remember and monitor an object's location on the basis of color, it is surprising that infants fail to attend to color alone to individuate objects until 11.5 months (Wilcox, 1999). One explanation for this inconsistency is that the objects in Oakes' study may have been defined not only by their color but also by their luminance. If so, Oakes' findings are consistent with infants' use of color (and luminance) to individuate objects by 7.5 months, as has been demonstrated here. Thus, the current study highlights the importance of taking into account luminance when investigating the impact of color in object processing just as others have drawn attention to its importance in studies of color perception in infants (e.g., Peeples & Teller, 1975; Teller et al., 2004).

In conclusion, these studies have shed light on the significance that infants place on color and luminance in both patterned and unpatterned objects when individuating. These results provide evidence that when color is paired with luminance information, these surface features are sufficiently salient to support object individuation in infants as young as 7.5 months and are consistent with our hypothesis that infants use features that are reliable indicators of distinct objects. This early sensitivity to surface information may provide an anchoring point from which infants' develop a more advanced awareness of color and luminance as indicators of distinct objects. As such, the outcome of these studies reveals new information about the features infants use to individuate objects and has implications about the nature and content of the object representations that infants form during occlusion events.

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