OBJECT INDIVIDUATION IN INFANCY:

THE VALUE OF COLOR AND LUMINANCE

A Dissertation

by

REBECCA JINDALEE WOODS

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2006

Major Subject: Psychology

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Approved by:

Chair of Committee,	Teresa Wilcox
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ABSTRACT

Object Individuation in Infancy: The Value

of Color and Luminance. (August 2006)

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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 until 11.5 months. However, color and luminance frequently co-vary in the natural environment, and color and luminance interact in pattern detection, motion detection, and stereopsis. 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, Experiments 1 and 2 assessed 7.5-month-old infants' ability to individuate uniformly colored objects that either varied in both color and luminance or varied in luminance alone. The results indicated that infants used these features to individuate only when the objects varied in both color and luminance. Thus, when color and luminance co-varied, infants used these features to individuate objects a full 4 months earlier than infants use either feature alone.

Experiment 3 further explored the link between color and luminance by assessing 7.5-month-old infants' ability to use pattern differences to individuate objects. Although infants use pattern differences created from a combination of luminance and color contrast by 7.5 months, results from Experiment 3 indicated that when pattern was created from either color contrast or luminance contrast alone, infants fail to individuate based on pattern. The results of Experiment 3 suggest that it is not the number of feature dimensions that is important, but the unique contribution of both color and luminance that is particularly salient to infants. 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.

DEDICATION

To Aricka, Amanda, and Austin,

and

To my mother, Melane

for a lifetime of support

ACKNOWLEDGEMENTS

I would like to thank my advisor, Teresa Wilcox, for her support, patience, and advice; John Mielke and Kristi Davis for their persistent encouragement; Tracy Smith, Veronica Gonzalez, Jennifer Armstrong, Sarah McCurry, Brenna Walker, and the undergraduate assistants of the Infant Cognition Laboratory at Texas A&M University for their help with data collection and their friendly companionship; and the parents who kindly agreed to have their infants participate in this research.

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INTRODUCTION

Visual examination of an object provides many different kinds of information about the object. Some of this information can be used to keep track of an object as it moves through space. For example, *object individuation*, the ability to determine whether an object is the same or a different object than one previously seen, can be based on differences or similarities in the features of objects. To illustrate, an object seen at one point in time may be small, round, smooth, and red. An object seen at a later time or in a different location may be large, irregularly shaped, and spotted. Shape, size, pattern, and color each convey information that suggests that these are two unique objects, distinct from one another.

The origins and development of the ability to use featural information to individuate objects has recently received a great deal of attention (Bonatti, et al., 2002; Flombaum, et al., 2004; Santos, et al., 2002; Van de Walle, Carey, & Prevor, 2000; Wilcox, 1999; Wilcox & Baillargeon, 1998a,b; Wilcox & Chapa, 2004; Wilcox & Schweinle, 2002; Woods & Wilcox, 2006; Wilcox, et al., 2006; Xu & Carey, 1996). One noteworthy finding is that infants are more sensitive to some types of information than others. For example, infants use shape information as a basis for object individuation long before they use color information (Wilcox, 1999). In various other object-related tasks, infants similarly draw on shape information but fail to make use of color information (object segregation- Needham, 1999; object identification-Tremoulet,

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This thesis follows the style of *Developmental Science.*

Leslie, & Hall, 2001).The focus of more recent research has been to learn how color can be made more salient by giving infants experience with the objects or colors (e.g., Wilcox & Chapa, 2004; Wilcox, et al., 2006). The objective of the current study was different in that we sought to increase infants' sensitivity to color information by examining the perceptual experience of object color and thereby obtain a more detailed analysis of infants' use of color to individuate objects.

Assessing object individuation in infancy

Many measures have been used to assess infants' ability to individuate objects, but by far the most frequently applied is the violation-of-expectation paradigm (Baillargeon, Spelke, & Wasserman, 1985). In the violation-of-expectation paradigm, infants are shown one of two events. One of these events has an expected outcome (one that is consistent with an adult's understanding of the event) and the other has an unexpected outcome (one that is inconsistent with an adults understanding of the event). If infants understand the event in the same manner as adults, then they should look longer at the unexpected outcome than at the expected outcome. This paradigm has been useful for investigating infants' knowledge of objects including object individuation.

One type of violation-of-expectation task that has been used to assess infants' ability to individuate objects is the narrow-screen task (Wilcox & Baillargeon, 1998a,b). Infants see two objects (e.g., a ball and a box) emerge successively to either side of a narrow or a wide screen. The wide screen is sufficiently wide to hide both objects simultaneously, but the narrow screen is not. If infants understand that two distinct objects are involved in the event, based on their featural differences, and understand that the combined width of the first object and the second object allows them to be simultaneously occluded by the wide, but not the narrow screen, then infants are expected to find the narrow-screen event surprising, as indicated by longer looking times. This task is a sensitive measure of infants' ability to individuate objects and it has been used to assess infants' use of a variety of object features for object individuation (e.g., Wilcox, 1999; Wilcox & Baillargeon, 1998a,b; Wilcox & Schwienle, 2002).

Hierarchies in infants' use of features to individuate objects

Using the narrow-screen task described above, Wilcox (1999) has revealed hierarchies in infants' use of individual object features. Wilcox tested infants' use of shape, size, pattern, and color as a basis for object individuation and found that infants are sensitive to shape and size by 4.5 months, but it is not until 7.5 months that infants attend to pattern information, and 11.5 months that infants attend to color information. These results are surprising because infants detect shape, size, pattern, and color much earlier than they are used to individuate objects (Aslin, 1987; Clavadetscher, et al., 1988; Dobson & Teller, 1978; Skoczenski, 2002; Slater, Mattock & Brown, 1990; Slater, Morison, & Rose, 1983; Teller & Bornstein, 1987). Why, if these features are detected, would infants fail to use them to individuate objects?

The two most feasible explanations for this hierarchy are based upon 1) infants' emerging visual capabilities, and 2) biases to attend to or use specific types of features. The first of these explanations suggests that the hierarchy seen in infants' ability to individuate objects based on features is reflective of the order in which infants detect those features. For example, shape and size information are detected prior to the detection of detailed pattern or color information (Aslin, 1987; Clavadetscher, et al., 1988; Dobson & Teller, 1978; Skoczenski, 2002; Slater, Mattock & Brown, 1990; Slater, Morison, & Rose, 1983; Teller & Bornstein, 1987). As a consequence, shape and size information are used to individuate objects prior to pattern and color information.

In contrast to an explanation based on visual detection, Wilcox (1999) proposed that when individuating, infants are biased to process information that is more intimately linked to the object, is more likely to accurately predict the outcomes of physical events, and is more stable over time. These features are more likely to determine the relationship between the object and their environment. She brings attention to the distinction between form features and surface features. Form features (e.g., shape and size) define the form of objects whereas surface features (e.g., pattern and color) describe the surface of objects. Shape and size are both detected at an early age and more reliably predict the outcomes of physical events. In contrast, pattern and color, are detected at a later age and are less intimately linked to the identity of an object, are less predictive, and are less stable over time than form features.

Woods and Wilcox (2006) presented 7.5- and 11.5-month-old infants with an individuation task designed to test the prediction of these two explanations by investigating infants' use of luminance as a basis for individuating objects. Luminance, as an object feature, is in the unique position of being detected early (at birth) while also being a surface feature and therefore less likely to predict event outcomes. Thus, if infants first attend to features that are detected early, infants should accordingly attend to luminance at an early age when individuating objects. In contrast, if infants are biased to attend to specific features that are more likely to determine the relationship between the object and their environment, infants should use luminance later because it is less stable and less likely to predict event outcomes or physical events. As with previous studies, the narrow-screen task was used. At 7.5 months, infants looked equally at the narrow- and wide-screen events in both different-luminance and same-luminance conditions. In contrast, 11.5-month-olds looked reliably longer at the narrow- than wide-screen event when objects seen to either side of the occluder differed in their luminance measures. Thus by 11.5 months, infants provide evidence that they attended to the luminance of objects and use that information to individuate. This outcome provides support for the explanation that infants attend to particular features that are more reliable for predicting event outcomes.

Facilitating color-based object individuation

Recent research has focused on the extent to which infants can be led to attend to the surface properties of objects under more supportive conditions. Most of this research has focused on learning what kinds of experiences with objects facilitate object individuation. The results of such studies have indicated that infants' use of color and pattern is not rigidly determined, but that infants can be led to attend to an object's surface features, if provided with select experiences.

For example, when infants saw an event in which an object's color was linked with its function, infants used color to individuate by 7.5 months (Wilcox & Chapa, 2004), whereas infants who did not see the event did not use color to individuate until 11.5 months (Wilcox, 1999). In this study, infants succeeded in extracting the relevance of the color information from pre-test pounding and pouring events in which color was associated with function. Similar results were obtained with younger infants when tested using pattern information. The results from this series of studies suggest that even very young infants can be primed to attend to surface features when individuating, provided that the relevance of those features is highlighted.

Other kinds of experiences with objects also facilitate individuation based on features. In segregation studies, simply having previous experience with the objects themselves influenced segregation (Needham & Baillargeon, 1998; Needham 2001; Needham, Dueker, & Lockhead, 2005). Recent research suggests that multi-sensory exploration of objects prior to test similarly benefits infants when individuating (Wilcox & Chapa, 2004; Wilcox, et al., 2006). When infants were allowed to visually, orally, and tactilely explore objects prior to test, they used color to individuate by 10.5 months. In contrast, when infants were allowed to explore the objects visually, but not orally or tactilely, they did not use color to individuate at 10.5 months.

In each of these studies, infants were given information about the objects or color more generally prior to being tested in an object individuation task. Through priming, infants became more sensitive to color information. The results of these studies are encouraging because they suggest that infants' ability to individuate objects based on color information is flexible and may be facilitated in various ways.

The current research

Another approach, that has not yet been tested, is to manipulate the perceptual experience of color in a way that will make it more salient to infants. What we commonly refer to as ‘color’ is the perceptual experience of light. This experience is composed of both the wavelength of light and its intensity. These two components create the experience of hue and lightness[1] respectively and can be varied independently of one another. Purely color differences occur only when lightness, as measured by luminance, remains constant. However, in the natural environment color frequently covaries with luminance. These two components of light are intricately intertwined and our experience of one can be influenced by the other (e.g., Farell, 1999; Gowdy, Stromeyer, & Kronauer, 1999; Hilz & Cavonius, 1970; Jordan, Geisler, & Bovik, 1990; Takeuchi, De Valois, & Hardy, 2003). Because they are so closely joined in our perceptual experiences, a rich environment that includes variations in both color and luminance can enhance perceptual and cognitive processing (e.g., Gegenfurtner & Rieger, 2000).

Previous studies investigating infants’ ability to individuate objects have examined infants’ use of either color differences alone (Wilcox, 1999) or luminance differences alone (Woods & Wilcox, 2006). However, considering the advantages gained from an environment composed of both color and luminance, it is important to take into account variations in both when studying object individuation. If an object differs in both color and luminance from one previously viewed, it is possible that infants will find this more salient than when objects differ along only one of these

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[1] The use of the term *lightness* is consistent with literature that describes the perceptual experience of luminance levels, independent from hue. This is different from *brightness,* which results from both hue and luminance (e.g., Teller, Pereverzeva, & Civan, 2003).

categories and therefore will individuate more readily than when objects differ in color or luminance alone.

The current research tested this possibility by assessing 7-month-old infants' ability to individuate objects based on color differences, luminance difference, or both using solid-colored or patterned objects using the narrow-screen task of Wilcox and Baillargeon (1998a,b). Three experiments were conducted. Experiments 1 and 2 used solid-colored objects. In Experiment 3, patterned objects were used. It was expected that infants would individuate objects at an earlier age based on co-variations of color and luminance than they would individuate objects based on color or luminance differences alone. Together, Experiments 1 and 2 suggest that 7.5-month-olds individuate solid-colored objects when both the color and the luminance vary, but not when luminance alone varies. The same was seen in Experiment 3 using patterned objects. When objects' patterns were created using color alone or luminance alone infants' failed to individuate objects based on pattern, but when the pattern was created using areas contrasting in both color and luminance, infants successfully individuated the objects (Wilcox, 1999).

EXPERIMENT 1

Previous studies have shown that infants do not use color alone or luminance alone to individuate objects until 11.5 months (Wilcox, 1999; Woods & Wilcox, 2006). The present research assessed 7.5-month-old infants' ability to individuate objects that differ in both color and luminance using the narrow-screen task of Wilcox and Baillargeon (1998a,b).

Infants were tested in two conditions: *green-red* and *orange-purple*. In each condition objects differed in both color and luminance, unlike previous studies in which objects differed in only color alone or luminance alone. In the green-red condition, infants saw a green ball and a red ball with different luminance measures emerge to opposite sides of either a narrow or wide screen (Figure 1). In the orange-purple condition, infants saw an identical event except that an orange ball and a purple ball, also differing in their luminance measures, were used. The narrow screen was too narrow to occlude both objects at the same time, whereas the wide screen was sufficiently wide to hide both objects simultaneously. If 7.5-month-old infants use color differences paired with luminance differences to specify the presence of distinct objects, correctly determine that both objects can be fully occluded by the wide, but not the narrow screen, then the infants should find the narrow-screen event unexpected or surprising as indicated by longer looking at the narrow- than wide-screen test events. Conversely, if infants fail to use the color and luminance information to individuate the objects, they should look equally at the narrow- and wide-screen test events.

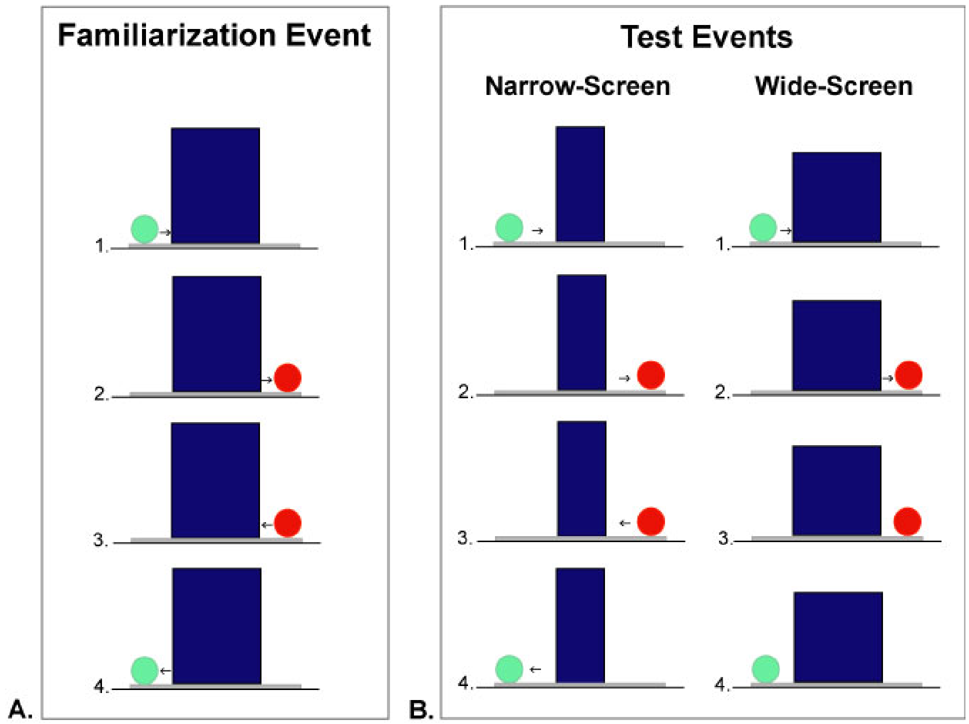

Figure 1 *Schematic drawing of the green-red familiarization event (A) and narrow- and wide-screen test events (B).*

Method

Participants

Thirty-six 7.5-month-old full-term, healthy infants were recruited from birth announcements and commercially produced lists (*M* = 7 months, 15 days; range = 6 months, 29 days to 8 months, 3 days). A priori power analyses indicated that this number of infants is sufficient to obtain power greater than 0.80 at an effect size equal to 0.80. Parents reported their infant's race/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: 3 due to fussiness, 3 due to the inability of the primary observer to determine the direction of the infants gaze, and 2 due to procedural problems. Nine infants (4 male, 5 female) were pseudo-randomly assigned to one of four groups formed by crossing color pair (green-red or orange-purple) with screen size (narrow or wide): green-red narrow screen (*M* = 7 months, 17 days), green-red wide screen (*M* = 7 months, 9 days), orange-purple narrow screen (*M* = 7 months, 18 days), orange-purple wide screen (*M* = 7 months, 17 days).

Apparatus and stimuli

The apparatus consisted of a wooden cubicle 213 cm high, 105 cm wide, and 43.5 cm deep. The floor and side walls were cream colored and the rear wall was covered with patterned contact paper. A muslin covered shade was lowered over the opening in the front wall of the apparatus at the end of each trial and remained lowered until the beginning of the following trial. A cream colored platform 1.5-cm tall, 60 cm wide, and 19 cm deep sat at the back of the apparatus, centered between the left and right walls. A strip of blue felt fabric lay lengthwise down the center of the platform to allow smooth and quiet movement of the objects. Two muslin-covered wooden frames, 214 cm high and 68 cm wide, stood at an angle to either side of the apparatus. These frames isolated infants from the experiment room and concealed two observers. Small peepholes in the muslin allowed observers to monitor infants' looking behavior. In addition to room lighting, four 20-W fluorescent bulbs were affixed to each of the inside walls of the apparatus 95 cm above the floor of the apparatus and concealed from sight.

The balls used in the familiarization and test events were made of painted Styrofoam, 10.25 cm in diameter. The luminance measures for each ball were: green 78 c/m^2, red 55 c/m^2, orange 78 c/m^2, and purple 48 c/m^2 (Figure 2). Each ball was mounted on a clear Plexiglas base, 10 cm wide, 6.5 cm deep and .3 cm thick with a handle 16 cm long. The handle of the Plexiglas base 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 left and right along the platform.

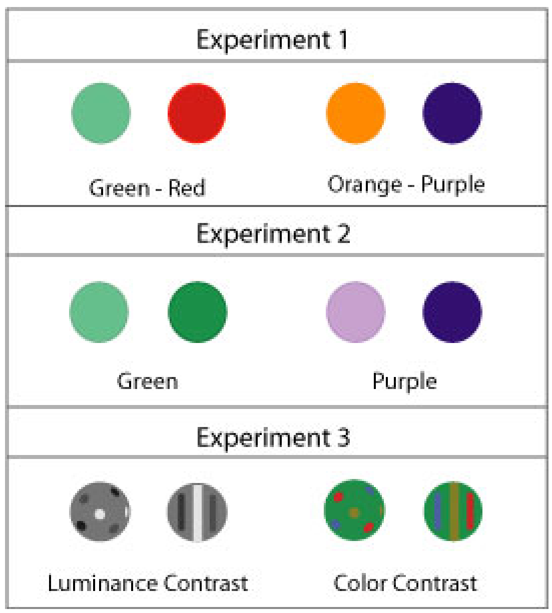

Figure 2 *Circles represent the stimuli used in each condition of Experiments 1 - 3.*

Embedded in the center of the platform was a metal bi-level shelf with an upper and lower level 16 cm apart; each shelf was 12.7 cm wide and 13 cm deep. The bi-level 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 screen used during familiarization trials consisted of a 30 cm wide and 41 cm high yellow matte board covered with clear contact paper. Narrow (15.5 x 41 cm) and wide (30 x 33 cm) test screens were made from dark blue matte board decorated with small gold stars and covered with clear contact paper. The screens were mounted on a wooden stand centered in front of the platform.

Events

Green-red narrow-screen condition

Familiarization event. At the beginning of each trial the familiarization screen sat upright and centered in front of the platform. The green ball sat 6 cm from the left end of the platform and the red ball rested on the lower shelf of the bi-level. Each familiarization trial began with a brief pretrial during which the observers monitored infants looking at the green ball until the computer signaled that the infant had looked at the ball for 1 s. The main trial followed, beginning with a 1-s pause. The green ball then moved to the right until it came to rest on the upper shelf of the bi-level (2 s). The bi-level was then lifted until the lower shelf was even with the platform (1 s) and the red ball moved to the right until it sat at the right end of the platform (2 s). After a 1-s pause, the red ball returned behind the screen to its initial position on the lower shelf of the bi-level (2 s) and the bi-level was lowered so that the upper level was even with the platform (1 s). The green ball then moved to the right from behind the screen to its original starting position at the left end of the platform (2 s). When in motion, the balls moved at about 12 cm/s. The entire event took 12 s and was repeated until the end of the trial.

Test event. The test event was identical to the familiarization event except that the familiarization screen was replaced with the narrow test screen.

Red-green wide-screen condition

The familiarization and test events in the red-green wide-screen condition were identical to those in the red-green narrow-screen condition except that the narrow test screen was replaced with the wide-test screen.

Orange-purple narrow- and wide-screen conditions

The familiarization and test events in the orange-purple narrow- and wide-screen conditions were identical to those in the green-red narrow- and wide-screen conditions, respectively, except that the green and red ball were replaced by the orange and purple ball, respectively.

Procedure

Infants sat on a parent's lap centered, facing an opening in the front wall of the apparatus. During the experiment the infant's head was approximately 80 cm from the objects on the platform. The parent was asked not to interact with the infant while the experiment was in progress and to close his or her eyes during each trial.

Each infant participated in a two-phase procedure consisting of a familiarization and test phase. During the *familiarization* phase, infants saw the familiarization event appropriate for their condition on six successive trials. 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. Each trial terminated when the infant (a) looked away for 2 consecutive seconds after having looked for at least 6 cumulative seconds or (b) looked for 60 cumulative seconds without looking away for 2 consecutive seconds. The infant's looking behavior was monitored by two naïve observers concealed by 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. The looking times recorded by the primary observer determined when a trial had ended and were used data analysis. Each trial was divided into 100 ms intervals, and the computer determined whether the two observers agreed on the direction of infant’s gaze. Inter-observer agreement was calculated for 35 of the infants (for 1 infant only one observer was available). Inter-observer agreement averaged 94% per test trial per infant.

Preliminary analysis of the infants’ mean looking times during the test trials did not yield significant gender differences, therefore the data were collapsed across sex in subsequent analysis.

Results

Familiarization trials

The infants’ looking times during the six familiarization trials (Figure 3) were averaged and compared by means of a 2 × 2 analysis of variance (ANOVA), with Color pair (green-red versus orange-purple) and Screen (narrow versus wide) as between subjects factors. The main effects of Color pair, $F(1,32) = 0.02$, and Screen $F(1,32) = 0.10$, were not significant nor was the Color pair × Screen interaction, $F(1,32) = 2.15$, indicating that the infants in the four different conditions did not differ reliably in their mean looking times at the 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).

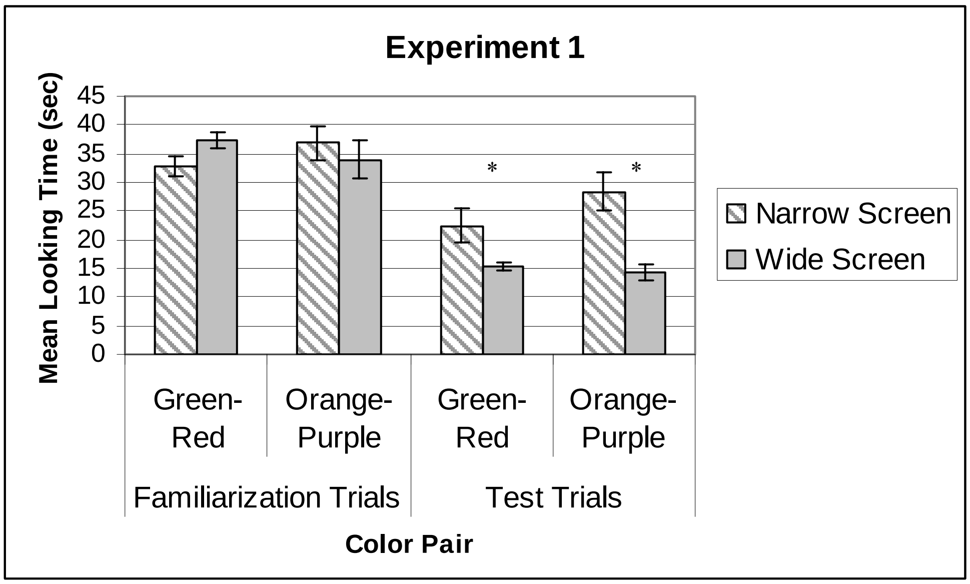

Figure 3 *Mean looking times of the 7.5-month-old infants in Experiment 1 during the familiarization and test trials.*

Test trials

Infants' mean looking times during the four test trials (Figure 3) were averaged and analyzed in the same manner as the familiarization trials. The Color pair × Screen interaction was not significant, $F(1,32) = 2.16$, nor was the main effect of Color pair, $F(1,32) = 1.12$. However, the main effect of Screen was significant, $F(1,32) = 20.03$, $P < 0.001$, $\eta_p^2 = 0.39$. Planned comparisons indicated that for each color pair, infants who saw the narrow-screen event looked reliably longer than those who saw the wide-screen event, $F(1,32) = 15.38$, $P = 0.001$ (green-red narrow screen, $M = 22.48$, $SD = 8.93$; green-red wide screen, $M = 15.43$, $SD = 2.19$, $F(1,32) = 5.31$, $P = 0.04$, Cohen's d = 1.08; orange-purple narrow screen, $M = 28.43$, $SD = 9.88$; orange-purple wide screen, $M = 14.46$, $SD = 4.06$, Cohen's $d = 1.85$).

Additional results

While it is clear from previous studies that infants do not use red-green color differences alone to individuate objects (Wilcox, 1999; Wilcox, et al., 2006), the same has not been demonstrated for an orange-purple color pair. Although unlikely, it is possible that orange and purple color differences are more likely to be individuated than red and green color differences. If so, this would mean that infants may have used color differences alone to individuate the orange and purple objects in Experiment 1. Although this was unlikely, we tested 20 additional 7.5 month-olds (M = 7 months, 20 days; range = 7 months, 0 days to 8 months, 5 days) using the same procedure as the orange-purple color pair in Experiment 1 with one exception: the orange and purple balls seen to either side of the familiarization and test screen were identical in luminance; only color varied. Looking times during familiarization trials were averaged and analyzed by means of a one-way analysis of variance (ANOVA) with test-screen type (narrow or wide) as the between-subjects factor. Results indicated that infants looked equally at the familiarization events for the narrow- ($M = 34.37$, $SD = 8.79$) and wide-screen conditions ($M = 36.11$, $SD = 4.46$), $F(1, 18) = 0.31$, $P = 0.58$. Looking times in test were analyzed in the same manner as familiarization trials. Results indicated that infants looked equally at the narrow- (M = 15.83, SD = 5.97) and wide-screen (M = 17.31, SD = 11.29) events, $F(1, 18) = 0.13$, $P = 0.72$. These results indicate that 7.5-month-old infants failed to use orange and purple color differences alone to individuate the objects. This suggests that infants who saw the orange-purple color pair of Experiment 1 used both color and luminance differences together to individuate the objects and did not individuate based on color differences alone.

Discussion

Results indicated that the infants in the green-red and orange-purple conditions looked longer at the narrow- than wide-screen test events suggesting infants used the differences in color and luminance to determine that two objects were involved in the events, and that both objects could be occluded by the wide, but not the narrow screen. Infants were therefore surprised by the narrow- but not the wide-screen event. One interpretation of these results is that when the objects differed in both color and luminance this difference was sufficiently salient to support infants' ability to use these surface features to individuate objects. When color differences alone are used or luminance differences alone are used, infants fail to individuate objects, but when both color and luminance vary infants succeed.

There is however, an alternative interpretation. Rather than using both color and luminance differences to individuate objects, infants are capable of using luminance differences alone providing stimuli are chromatic, as opposed to achromatic. Thus it is not variations of both color and luminance that is important, it is seeing luminance differences on chromatic objects that leads to increased sensitivity to luminance differences. Experiment 2 addresses this possibility.

EXPERIMENT 2

To assess infants' ability to use a luminance change without a color change on chromatic objects, infants aged 7.5 months were tested using the same procedure as was used in Experiment 1, except that the objects seen to either side of the screen differed only in luminance while color remained constant. If the advantage gained is a result of co-variations in both color and luminance, we expected that infants would fail to individuate objects based on luminance differences alone, even if those differences occurred on objects that were colored.

Method

Participants

Thirty-six 7.5-month-old infants were recruited from birth announcements and commercially produced lists (*M* = 7 months, 18 days; range = 7 months, 1 day to 8 months, 3 days). Parents reported their infant's race/ethnicity as Caucasian (*N* = 25), Hispanic (*N* = 4), Asian (*N* = 2), or of mixed race (*N* = 5). Two additional infants were tested but removed from analysis: 1 due to fussiness and 1 because the parent reported a familial history of colorblindness.[2] Nine infants (5 male, 4 female) were pseudo-randomly assigned to each of the four experimental groups formed by crossing color pair

[2] In Experiments 2 and 3, parents were asked to report family history of color blindness. Males were eliminated from analysis if color blindness was reported for a member of the mother's immediate family. Females were eliminated from analysis if color blindness was reported for a member of the mother's immediate family and if the biological father was color blind.

(green or purple) with screen size (narrow or wide): green narrow screen (M = 7 months, 19 days), green wide screen (M = 7 months, 17 days), purple narrow screen (M = 7 months, 18 days), purple wide screen (M = 7 months, 19 days).

Apparatus and stimuli

The apparatus and stimuli were identical to that of Experiment 1, with one exception. The balls seen to either side of the familiarization and test screens had different color and luminance measures than those of Experiment 1. One pair of balls was colored green with luminance measures of 78 c/m^2 and 55 c/m^2. The other pair was colored purple with luminance measures of 69 c/m^2 and 48 c/m^2 (Figure 2).

Events

Green narrow- and wide-screen conditions

The familiarization and test events in the green narrow- and wide-screen conditions were identical to those in the narrow- and wide-screen conditions seen in Experiment 1, except that the green ball with the highest luminance measure (lightest) was seen to the left of the screen and the ball with the lowest luminance measure (darkest) was seen to the right of the screen. The lighter ball was lifted by the top shelf of the bi-level and the darker ball emerged from the lower shelf.

Purple narrow- and wide-screen conditions

The familiarization and test events in the purple narrow- and wide-screen conditions were identical to the green narrow- and wide-screen conditions except that the green balls were replaced by the purple balls.

Procedure

The procedure used in Experiment 2 was identical to that used in Experiment 1. Inter-observer agreement was measured for 33 of the infants and averaged 92% per trial per infant. Preliminary analysis of the infants' mean looking times during the test trials did not yield a significant gender differences, therefore the data were collapsed across sex in subsequent analysis.

Results

Familiarization trials

The infants' looking times during the six familiarization trials (Figure 4) were averaged and compared by means of a 2 × 2 ANOVA, with Color pair (green versus purple) and Screen (narrow versus wide) as between subjects factors. The main effects of Color pair, $F(1,32) = 1.70$, and Screen $F(1,32) = 0.10$, were not significant nor was a Color pair × Screen interaction, $F(1,32) = 0.09$, indicating that the infants in the four different conditions did not differ reliably in their mean looking times at the familiarization trials (green narrow screen, $M = 34.99$, $SD = 8.55$; green wide screen, $M = 34.95$, $SD = 6.40$; purple narrow screen, $M = 32.57$, $SD = 8.53$; purple wide screen, $M = 31.09$, $SD = 4.63$).

Test trials

Infants' mean looking times during the four test trials (Figure 4) were averaged and analyzed in the same manner as the familiarization trials. Neither the main effect of Color pair, $F(1,32) = 0.09$, nor Screen were significant, $F(1,32) = 2.10$, nor was an interaction between Color pair and Screen, $F(1,32) = 0.02$, indicating that for each color pair, infants looking times at the narrow- and 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* = 20.86, *SD* = 11.32; purple wide screen, *M* = 16.40, *SD* = 5.93). Although there was a trend in the expected direction, effect size for Screen was exceedingly small, $\eta_p^2 = 0.06$, notably smaller than that of Experiment 1, $\eta_p^2 = 0.39$.

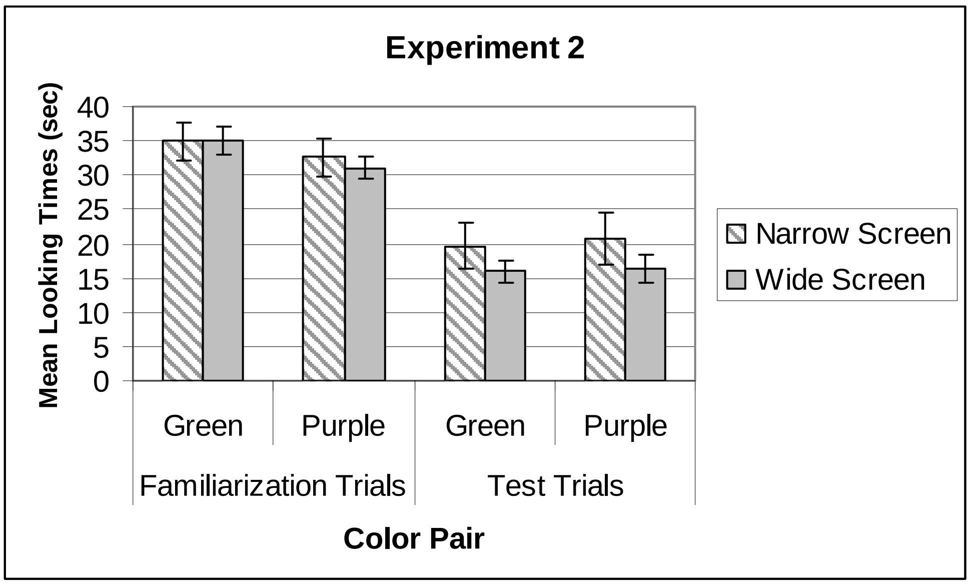

Figure 4 *Mean looking times of the 7.5-month-old infants in Experiment 2 during the familiarization and test trials.*

Discussion

In contrast to the positive results obtained when both object color and luminance differed (Experiment 1), infants who saw objects that were chromatic but differed in luminance (Experiment 2) looked equally at the narrow and wide screen events suggesting that they failed to use the luminance difference to individuate the objects.

These results suggest that even when objects are chromatic, luminance differences alone are not sufficient to support object individuation. It is only when both color and luminance vary together that 7.5-month-old infants succeed in using these features to individuate objects.

There are two reasons that varying both color and luminance may facilitate object individuation. One is that the amount of information signifying the presence of distinct objects has been increased (objects differ along two dimensions rather than one). A second possibility is that it is not the quantity of information that is important, but that the combination of color and luminance is uniquely special. Experiments 3 addresses the second of these possibilities by investigating 7.5-month-old infants' ability to individuate objects based on pattern differences that are created using variations in color alone or luminance alone. Studying pattern is ideal for examining the qualitative nature and interaction between color and luminance because these two properties can be manipulated while permitting individuation to be based on a single feature (i.e., pattern). In addition, there is evidence that the combination of color and luminance has a facilitative effect on pattern detection in adults. For example, adding luminance lowers the threshold for detection of a colored pattern and conversely, adding color lowers the threshold for detection of a luminance pattern, although to a lesser extent (Gowdy, Stromeyer, & Kronauer, 1999). It is possible that the combination of color and luminance contrast will similarly enhance the ability to determine whether an object is the same or different than one previously viewed based on pattern differences.

EXPERIMENT 3

Wilcox (1999) demonstrated that 7.5-month-olds successfully individuate objects based on a pattern difference created using areas of contrasting color and luminance measures. Infants' ability to individuate objects based on pattern was assessed using the narrow-screen task. The objects used consisted of a dotted ball and a striped ball that differed from one another only in their pattern. The dotted ball was painted green with dots that varied in both color (i.e., yellow, blue, and red) and in luminance. The striped ball was identical in every way to the dotted ball, except that instead of dots, it had stripes. The patterns of both objects were created using areas contrasting in both color and luminance. Experiment 3 assessed 7.5-month-olds' ability to use these same pattern differences to individuate objects that were either achromatic or isoluminant. Thus, in one condition, the objects' pattern was created using only luminance contrast and in another condition, the objects' pattern was created using only color contrast (Figure 2).

Method

Participants

Thirty-six 7.5-month-old infants were recruited from birth announcements and commercially produced lists (*M* = 7 months, 16 days; range = 6 months, 29 days to 8 months, 4 days). Parents reported their infant's race/ethnicity as Caucasian (*N* = 28), Hispanic (*N* = 3), or 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 pseudo-randomly assigned to one of the four experimental groups formed by crossing pattern (luminance contrast or color contrast) with screen size (narrow or wide):

luminance contrast narrow screen (*M* = 7 months, 16 days), luminance contrast wide screen (*M* = 7 months, 16 days), color contrast narrow screen (*M* = 7 months, 10 days), color contrast wide screen (*M* = 7 months, 20 days).

Apparatus, stimuli, events and procedure

The apparatus of Experiment 3 was identical to that of Experiment 1 and 2. The stimuli used were identical to those used in Experiment 1 and 2 except that one pair of balls seen to either side of the screen were achromatic dotted and striped and the other pair of balls were chromatic, iso-luminant dotted and striped balls (Figure 2). The dotted ball was seen resting on the platform to the left of the screen at the beginning of each trial. Inter-observer agreement was measured for each infant and averaged 93% per trial per infant.

Preliminary analysis of the infants' mean looking times during the test trials did not yield a significant gender differences, therefore the data were collapsed across sex in subsequent analysis.

Results

Familiarization trials

The infants' looking times during the six familiarization trials (Figure 5) were averaged and compared by means of a 2 × 2 ANOVA, with Pattern (luminance contrast versus color contrast) and Screen (narrow versus wide) as between subjects factors. The main effects of Pattern, $F(1,32) = 0.22$, and Screen $F(1,32) = 0.36$, were not significant nor was a Pattern × Screen interaction, $F(1,32) = 0.11$, indicating that the infants in the four different conditions did not differ reliably in their mean looking times at the 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).

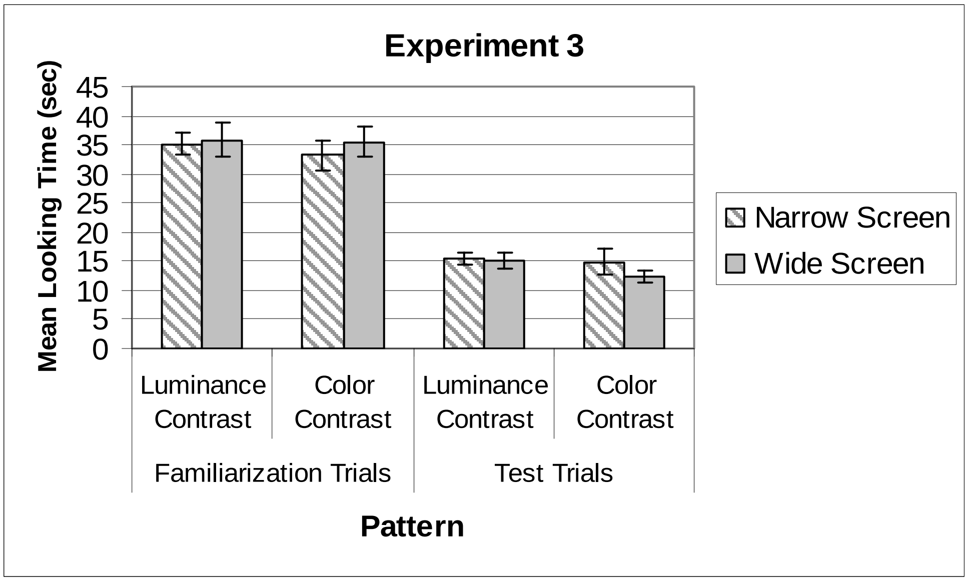

Figure 5 *Mean looking times of the 7.5-month-old infants in Experiment 3 during the familiarization and test trials.*

Test trials

Infants' mean looking times during the four test trials (Figure 5) were averaged and analyzed in the same manner as the familiarization trials. Neither the main effect of Pattern, $F(1,32) = 1.26$. nor Screen were significant, $F(1,32) = 0.88$, nor was an interaction between Pattern and Screen, $F(1,32) = 0.59$, indicating that for each pattern type, infants looked equally at the narrow- and wide-screen 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 objects differed in patterns created using a luminance contrast (color remained constant) or a color contrast (while luminance remained constant), infants failed to individuate the objects.

Additional analyses

To directly test the hypothesis, additional analyses compared results from Wilcox (1999), in which patterns were created using both color and luminance contrasts, to the results from Experiment 3. Data from twelve 7.5-month-olds (*M* = 7 months, 19 days; range = 7 months, 4 days to 8 months, 3 days) were taken from Experiment 3b of Wilcox (1999). The events seen were identical to the color-contrast and luminance-contrast, narrow- and wide-screen events seen in Experiment 3 with one exception: the objects seen to either side of the familiarization and tests screens consisted of a dotted ball and a striped ball created from both color and luminance contrast.

Looking times during familiarization trials were averaged and analyzed by means of a 3 X 2 analysis of variance (ANOVA) with Pattern (color contrast, luminance contrast, or both color and luminance contrast) and Screen (narrow or wide) as the between-subjects factors. The main effects of Pattern, $F(1,42) = 0.16$, and Screen $F(1,42) = 0.20$, 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 at 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, $M = 35.52$, $SD = 7.42$).

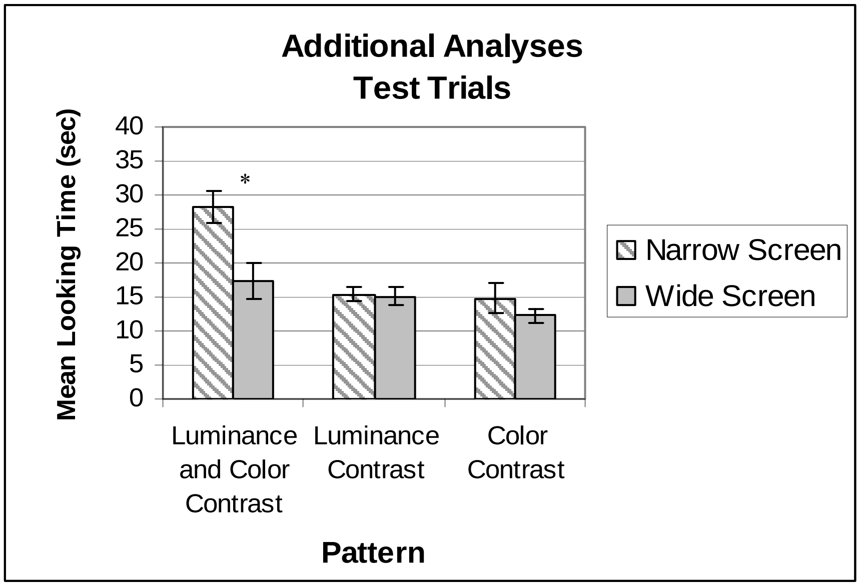

Figure 6 *Mean looking times during the test trials of the 7.5-month-old infants in additional analyses of Experiment 3.*

Looking times in test were analyzed in the same manner as familiarization trials (Figure 6). The main effects of Pattern, $F(1,42) = 13.54$, $P < 0.001$, $\eta_p^2 = 0.39$ and Screen $F(1,42) = 9.90$, $P = 0.003$, $\eta_p^2 = 0.19$ were significant as was the Pattern × Screen interaction, $F(1,42) = 4.38$, $P = 0.02$, $\eta_p^2 = 0.17$. Planned comparisons indicated that when pattern was created using both color and luminance contrasts, infants looked reliably longer at the narrow- ($M = 28.27$, $SD = 5.73$) than wide-screen event ($M = 17.47$, $SD = 6.51$), $F(1,42) = 14.30$, $P < 0.001$. These results indicate that 7.5-month-old's use pattern differences to individuate objects only when the pattern is created using areas contrasting in both color and luminance.

Discussion

When objects differed in pattern, whether created from a luminance contrast or color contrast, infants looked equally at the narrow- and wide-screen test events indicating that they failed to use the pattern differences to determine that two objects were involved in the event. These results contrast with previous data collected by Wilcox (1999) that suggest that infants use pattern differences to individuate objects when pattern is created using areas contrasting in both color and luminance. Experiment 3, unlike Experiments 1 and 2 manipulated color and luminance while varying a single object feature (i.e., pattern). The results of this study suggest that the combination of color and luminance play a unique contribution in infants' ability to use these features to individuate objects.

CONCLUSIONS

Three experiments were conducted to assess infants' sensitivity to color and luminance information during object individuation. Results revealed that when objects differ in both color and luminance, infants individuate objects much earlier than when color information is used alone, or when luminance information is used alone. This outcome occurred for both solid and patterned objects. These studies provide new evidence that dual processing of color and luminance can have facilitative effects on object individuation and reveal interesting information about the nature of the representations that infants hold.

The first two experiments examined 7.5-month-old infants' ability to individuate uniformly colored objects. Results suggested that when objects varied in both color and luminance, infants successfully determined that two objects were involved in the event. These results are in contrast to earlier studies showing that it is not until 11.5 months that infants use color differences to individuate objects while holding luminance constant (Wilcox, 1999) or luminance differences while holding color constant (Woods & Wilcox, 2006). Why would varying both color and luminance facilitate object individuation?

Color and luminance are more salient together

Color and luminance are intimately linked in the natural environment. These two features frequently co-vary, and it is evident that they interact in pattern detection (Cole, Stromeyer, & Kronauer, 1990; Gur & Syrkin, 1993; Hilz & Cavonius, 1970; Nagy & Kamholz, 1995), motion detection (Farell, 1999; Palmer, Mobley, & Teller, 1993;

Takeuchi, De Valois, & Hardy, 2003), and stereoscopic efficiency (Jordan, Geisler, & Bovik, 1990). The research presented here also suggests that together color and luminance form a unique combination that facilitates object individuation. It is likely that this is a result of the intimate link between these features in processing and in our perceptual experiences. Although it is possible that infants individuate objects when both color and luminance vary because varying two features is more advantageous than varying one, testing this prediction would be difficult. It is challenging, particularly in infants, to determine how distinct two objects are regardless of whether they differ within a single feature dimension (e. g., shape) or differ along two or more feature categories (e.g., shape and color). A more suitable approach is to focus not on the number of features that vary, but on the unique contribution of color and luminance to the individuation process.

Experiment 3 addresses the qualitative aspect of this interaction by isolating luminance and color while varying a single object feature (i.e., pattern), rather than multiple features. Results indicated that infants failed to individuate based on pattern differences when luminance contrast alone was used to create the objects' pattern and similarly failed when color contrast alone was used. These results are noteworthy when compared to previous data indicating that infants individuated objects based on pattern differences when both color and luminance contrasts were used to create the objects' patterns (Wilcox, 1999). These results provide support for the hypothesis that the interaction between color and luminance is sufficiently salient to support object individuation by 7.5 months. One explanation for this advantage is that color and luminance are closely linked in the neural processing of light information. This possibility is discussed in the next section.

Neural processing of color and luminance information

Early in visual processing, color and luminance information are separated and processed through different channels. Processing of light, both wavelength (color) and intensity (luminance), begins at the retina. Three cone types, located within the retina, are maximally responsive to short-, medium-, and long-wavelengths (S-, M-, and L-wavelengths, respectively). Signals are relayed from the cones to outer layers of cells located within the retina. Input from the retinal ganglion cells creates a color-opponent system along two axes: a red/green (L/M) axis and a blue/yellow (S/L+M) axis. A separate achromatic channel is formed when cone contributions are summed by parasol ganglion cells.

Information is then projected to different areas of the lateral geniculate nucleus (LGN) of the thalamus. At the LGN, much of the information conveyed by color and luminance travels through two largely independent streams (Livingstone & Hubel, 1987, 1988) that process both color and luminance information, but in two different ways (e.g., Dobkins & Albright, 1993). In primates, the LGN is divided into parvocellular and magnocellular layers, in addition to the more recently identified koniocellular layer (e.g., Hendry & Reid, 2000). The magnocellular layers have been regarded as more sensitive to contrast and have a fast conduction velocity resulting in good temporal resolution, suggesting that they are highly involved in motion processing based on contrast information. It has been argued that the magnocellular stream extracts contrast from color and luminance information, but does not code for the qualities of the color or luminance themselves (Dobkins & Albright, 1994, 1998; Lee et al., 1988). Cells located in the parvocellular layers have traditionally been regarded as more sensitive to wavelength and spatial resolution and are therefore associated with processing of color and fine detail. Within the parvocellular layer the quality of color information is coded, giving rise to color as a surface property.

In addition, recent identification of the koniocellular pathway has sparked a great deal of research to identify the primary purpose of this layer consisting of numerous, but tiny cells (Dobkins, 2000; Hendry & Reid, 2000). There is support that parts of the koniocellular layer are involved in color processing, particularly of blue (S-wavelengths) and yellow (L + M- wavelengths) light. In addition, there is evidence that input from the koniocellular pathway contributes to motion processing based on color contrast.

Information from each of these three pathways is projected to layers of the primary visual cortex (V1). Interestingly, in V1 and V2, not only are many cells selective to either luminance processing or color processing, but a large majority of these cells are responsive to both luminance and color (discussed in Gegenfurtner & Kiper, 2003). This joint sensitivity provides a neural mechanism to explain why color and luminance information are so intimately linked in our perceptual experiences. From area V1, color and luminance information (as surface properties) is thought to continue into the ventral or “what” pathway. This pathway is said to process information about the identity of an object including shape, size, and color (Ungerleider & Mishkin, 1982). In contrast, a separate pathway, the dorsal or “where” pathway is reported to process information about object motion and where objects are located in space.

It has been argued that infants are poor at integrating information from these two streams (Mareschal, Plunkett, & Harris, 1999). If infants have difficulty integrating these streams, information that is processed by both streams will have an advantage when infants are keeping track of objects (Johnson, Mareschal, & Csibra, 2001). Shape information, which is available to both streams, is more likely to be used to keep track of objects than color, which, it has been suggested, is processed almost entirely by the ventral stream.

Object processing during occlusion events, such as those in the current study, require infants to keep track of moving objects, thus requiring substantial use of the dorsal processing stream. Because the ventral and dorsal streams are less likely to be integrated in infants, object processing requiring heavy activation of the dorsal pathway may fail to fully incorporate ventral information in later processing. If this were the case, surface color or lightness information will be omitted or degraded. This would result in incomplete object representations and may be partially responsible for the delay in infants’ use of color information alone or luminance information alone when individuating moving objects. A lack of integration between the dorsal and ventral pathways would also explain why infants have been found to bind color and luminance when objects are stationary (Bushnell & Roder, 1985; Slater, et al., 1996), but have difficulty when objects are moving (Burnham, et al., 1988).

However, this may not entirely preclude the processing of color information. Inputs from both luminance and color sensitive cells can give rise to motion perception, indicating that color information is maintained even when demands on dorsal processing are high. Gegenfurtner and Hawken (1996) have argued that there are two functional processing streams for motion. One is fast and accurately provides information about the velocity of moving stimuli, even from isoluminant (color only) patterns, but does not code the color of the patterns. Another pathway codes the color of patterns, but is slower and does not provide accurate information about the velocity of moving stimuli. Recent investigations on the relation between color and motion processing in monkeys and psychophysical studies on adults have supported similar arguments and suggest that arguments for entirely distinct systems for color and motion processing may be tenuous (e.g., Dobkins & Albright, 1993, 1994; Mullen & Boulton, 1992; Palmer, Mobley, & Teller, 1993; Takeuchi, De Valois, & Hardy, 2003).

Even in infants, psychophysical studies suggest that color information can contribute to motion processing. Like adults, infants as young as 2 and 3 months of age discriminate isoluminant moving grating patterns (Dobkins, Lia, & Teller, 1997; Teller, 1998) suggesting that infants can detect motion from strictly color inputs. In fact, there is some evidence that infants possess better motion processing based on color stimuli than do adults (Dobkins & Anderson, 2002). It is clear that both color and luminance contrast information can give rise to the perception of motion. However, deficits from the combination of color and motion processing may still occur. For example, when stimuli are in the form of objects, it was noted that infants had a difficult time detecting moving targets that were defined entirely by color contrast (Ross & Dannemiller, 1999). For this reason, when objects are moving it is advantageous for color to be combined with luminance because together these features provide a more complete perceptual experience than is created from color contrast alone.

While it is clear that the neural processing of color and luminance differs in many ways, there are multiple stages at which color and luminance information are processed together. Dual processing can give co-variations of luminance and color information an advantage over variations in color alone or luminance alone by ensuring that color and luminance information are perceptually linked, and as a result, when processing deficits occur in one area, they are overcome by proficient processing in the other. This advantage is reflected in the current study. Not only does the current study provide further evidence to support an advantage for co-variations of color and luminance, but it also reveals information about the content of infants' object representations.

Object individuation and object representations

The ability to individuate objects requires infants to sustain some sort of mental representation of an object while it is out of view and use this representation to compare objects (whether the same or different) on subsequent encounters. As a consequence, questions regarding object representations have remained persistent in the object individuation literature. Specifically, what kind of representation is necessary to support object individuation and what does this tell us about the kinds of object representations infants possess more generally?

One question that has remained unanswered is the extent to which infants include color and luminance information in their object representations. The results of the current study provide evidence that infants must include some form of color and luminance information in their representations and when objects vary in both color and luminance, infants are led to use this information when individuating objects. When objects do not vary in both color and luminance, but vary in color alone or luminance alone, at 7.5 months infants do not use the color and luminance information that they carry in their representations. To better understand this reasoning, the following sections will outline the steps involved during an occlusion sequence and furthermore discuss how color and luminance may be involved at each step.

For simplicity, I will divide the occlusion sequence into three stages. The first stage occurs when an infant views an object. The object must be accurately perceived and encoded via visual inspection and the formation of an object representation takes place. This stage involves attention to particular features and encoding of particular kinds of information. The second stage occurs when the object is removed from view. During this time, an object representation must be maintained, requiring memory. The third stage occurs when a new (or the same) object comes into view. Like the first object, this object must be accurately perceived and encoded. In addition, the representation of the first object must be brought forth and compared to the current percept along particular variables (e.g. color, shape, pattern). It is at this point, that the visible object is determined to be the same or a different object based on similarities or differences between the current information and the information contained in the representation of the previously viewed object. If a particular feature is not included at any of these stages, it will not be used to individuate objects.

The key step in this sequence is step three. Object individuation occurs when infants compare the current object to an object representation and, if the features are different, determine that the object seen is a different object than the one seen previously. If for any reason, a specific type of information is not included in the object representation, it will not be compared to the current percept and individuation will fail.

Results from the current study suggest that both color and luminance information must have been included in the object representation because infants succeeded at individuating. This occurred without priming or any other experience with the objects that might lead them to include this information. To illustrate, consider the green ball described in Experiment 1. In the first stage of the occlusion event, infants code both the color and the luminance of the green ball. As the ball moves behind the screen, infants maintain color and luminance information in a representation. Then, a ball differing from the green ball in both color and luminance (i.e., the red ball) emerges from behind the screen. Infants compare the representation of the green ball to the representation of the red ball and use differences in color and luminance to determine that two objects were seen. Infants must have included a representation of both color and luminance to make this distinction. Had no color or luminance information been included in memory during occlusion, only shape and size information would have been carried in the object representation. Because shape and size information are identical for each object, infants would have concluded that a single objects was involved in the event.

These results contrast those of Experiment 2. In Experiment 2, a green ball identical to the green ball in Experiment 1 moved behind the screen. As a consequence, Experiment 1 and Experiment 2 were identical until the second object emerged from behind the screen. We presume that the information carried in memory was also identical (if the object moving behind the screen was identical, why would the memory of it differ?). The color and luminance of the green ball was held was memory as evidenced by Experiment 1. In Experiment 2, infants simply failed to indicate that they held this information in memory. This suggests that by 7.5 months, infants hold color and luminance information in representational form that is somehow carried with the representation of an object. This brings up several questions. For example, in what form are color and luminance information represented and, if they are included in memory, why are they not used to individuate objects when only color varies or luminance varies?

Color and luminance information in representations

Although color and luminance information must necessarily be maintained in memory, it is unclear how this information is represented. One possibility is that infants have complete object representations that include strong, entirely bound color and luminance information, yet they fail to use that information when comparing the object representation to the visible object. Another possibility is that color and luminance information are carried in memory, but they are not bound to the object representation.

Bound representation of color and luminance

One possibility is that infants' representations of color and luminance are initially entirely bound to the object representation. If this were so, it would suggest that infants fail to compare color or luminance information of the object representation to the visible object during the third step of the occlusion sequence, despite carrying a cohesive representation of object color and luminance in memory. This possibility, however lacks support.

Even in adults, studies investigating change detection suggest that *change blindness*, failure to detect a change, most likely results from incomplete representations of the items carrying the change (Beck & Levin, 2003; Levin, et al., 2002). Occlusion is included in the various methods for assessing change blindness (Rich & Gillam, 2000) making it highly relevant to individuation studies using occlusion. We suspect that like adults, infants fail to detect differences in color or luminance as a result of an incomplete representation, not as a failure to accurately compare a complete representation to the current object percept.

Abstract representation of color and luminance

It is more likely that infants do not initially bind color or luminance to an object representation, but are able to carry color and luminance information in a more abstract representational form during occlusion. This idea is consistent with theories describing features as processed separately and then bound in a single percept (e.g, Humphreys & Riddoch, 2006; Treisman & Gelade, 1980; Zeki, 1993). A good deal of research supports this perspective.

For example, studies investigating perception of objects in adults with both normal and deficient visual processing, and in studies investigating the underlying neurophysiology of these phenomena provide supportive evidence that features are initially processed independently. For instance, under certain conditions, adults with normal vision have been shown to incorrectly perceive objects. For example, *illusory conjunctions* occur when stimuli are incompletely attended resulting in features that are interchanged or inappropriately assigned to a stimulus (e.g., participants report seeing a green chair when they actually saw a green table and a yellow chair) (Treisman & Schmidt, 1982).

Evidence of independent processing also comes from disorders of visual object recognition. After sustaining damage to specific areas of the brain, patients have reported deficits in the ability to process individual features, such as color, while the processing of other features, such as shape, remained intact (Heywood & Cowey, 1999). Studies, such as these, fit nicely with neurophysiological evidence that early in visual processing, object features are dealt with along independent streams (Livingstone & Hubel, 1987; 1988).

This research supports the possibility that color (and luminance) information, while maintained in memory, may not necessarily be bound to the object representation. Particularly in infancy, when information processing resources are limited, certain types of information may be given priority for particular tasks. It is those features that are first bound to the object representation while other features are not. Information about color or luminance may be less likely to be included in an object representation because, unlike other features, such as shape or size, color and luminance are arbitrarily linked to objects and may change over time or under different lighting conditions.

However, to successfully individuate objects, color and luminance information must become bound to the object representation at some point, perhaps through increased visual attention. Attention has been thought to account for accurate binding of different features of objects in object perception (Treisman, 1998; Treisman & Gelade, 1980) and in the representations of objects (Wheeler & Treisman, 2002). If attention is required to bind color and luminance to an object representation, perhaps there is a threshold that must be met for these features to enter into the 'spotlight' of visual attention. When an object is encountered that differs from a previously seen object in color alone, activation differences do not meet this threshold. The same can be said of luminance differences. However, when objects differ along both dimensions, the sum of both luminance and color differences pushes activation above threshold bringing those features to the attention of infants. Once attention is brought to the surface features of the object those features which had previously been maintained only in an abstract form are more completely bound to the object representation.

This idea is consistent with the studies discussed earlier in which infants' ability to individuate objects based on color was increased when infants were primed to attend to color or pattern (Wilcox & Chapa, 2004). In those studies, increased attention to color may have facilitated the binding process.

Concluding remarks

The current study provides evidence that variations in both color and luminance are sufficiently salient to support object individuation in 7.5-month-old infants. These results highlight the benefits of dual processing of color and luminance information in an environment in which color and luminance co-vary. Advantages gained by processing both color and luminance differences may have resulted in raising neural activation above a critical threshold required for attention, enabling infants to bring both color and luminance information to bear when individuating objects.

In addition, this study provides evidence that by 7.5 months, infants maintain some sort of representation of color and luminance and are capable of incorporating this information in their object representations. While it is unclear how infants represent color and luminance, it is likely that infants do not initially bind color to the object representation, but that color information is carried in a more abstract representational form throughout occlusion which may be bound as a result of increased attention to these features. If so, it remains to be determined precisely at what point across familiarization trials infants begin to incorporate color and luminance into their object representation. It is also unclear whether results such as these are specific to color and luminance because they are so uniquely combined in our perceptual experiences, or whether similar results may be obtained using other surface properties. Future research will be directed toward learning how color and luminance information are held in memory and learning the mechanisms involved when infants' sensitivity to these features is increased.

These studies have shed light on the significance that infants place on color and luminance in both patterned and un-patterned objects when individuating. The natural interaction of these features in the environment, and other studies indicating that this interaction has a facilitative effect in perceptual and cognitive processing (e.g., Gegenfurtner & Rieger,2000; Gowdy, Stromeyer, & Kronauer, 1999; Gur & Syrkin, 1993) and suggest that studying the relation between color and luminance is relevant to investigations of infants' use of features in object processing.

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Research Interests

- Infants' use of object features, such as shape, color, or pattern
- Developmentally related changes in infants' use of particular features and the mechanisms that underlie these changes
- Development of object individuation in infancy
- Interactions between cognitive development and experience
- Relations between neural processing and behavioral measures of infants' use of particular object features

Selected Publications

Woods, R. J., & Wilcox, T. (2006). Infants' ability to use luminance information to individuate objects. *Cognition,* **99**, B43-B52.

Wilcox, T., & Woods, R. (2006). Experience primes infants to individuate objects: Illuminating learning mechanisms. To appear in *Learning and the Infant Mind* (A. Needham & A. Woodward, Eds), (in press).