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Multisensory Exploration and Object Individuation in Infancy

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Recent research indicates that by 4.5 months, infants use shape and size information as the basis for individuating objects but that it is not until 11.5 months that they use color information for this purpose. The present experiments investigated the extent to which infants' sensitivity to color information could be increased through select experiences. Five experiments were conducted with 10.5- and 9.5-month-olds. The results revealed that multimodal (visual and tactile), but not unimodal (visual only), exploration of the objects prior to the individuation task increased 10.5-month-olds' sensitivity to color differences. These results suggest that multisensory experience with objects facilitates infants' use of color information when individuating objects. In contrast, 9.5-month-olds did not benefit from the multisensory procedure; possible explanations for this finding are explored. Together, these results reveal how an everyday experience—combined visual and tactile exploration of objects—can promote infants' use of color information as the basis for individuating objects. More broadly, these results shed light on the nature of infants' object representations and the cognitive mechanisms that support infants' changing sensitivity to color differences.

Keywords: object individuation, color, infant cognition, multimodal processing

The visual world is dynamic and complex. When an object, an observer, or both move about in the world, visual contact with objects is often lost and then regained. One of the primary tasks of visual cognition is to determine whether an object currently in view is the same object as or a different object from one seen before. This capacity, referred to as object individuation, allows humans to represent the world in terms of numerically distinct objects that persist in space and time and influences how we think about and interact with objects. Given the importance of object individuation to human cognition, a great deal of effort has been expended to identify the origins and development of this capacity (e.g., Aguiar & Baillargeon, 2002; Bonnatti, Frot, Zangl, & Mehler, 2002; Krojgaard, 2000; Spelke, Kestenbaum, Simons, & Wein, 1995; Tremoulet, Leslie, & Hall, 2001; Van de Walle, Carey, & Prevor, 2000; Wilcox, 1999; Wilcox & Baillargeon, 1998a, 1998b; Wilcox & Schweinle, 2002, 2003; Xu, 2002; Xu & Carey, 1996). Much of this research has focused on the kind of information infants use to individuate objects and how this information changes during the 1st year of life.

The Development of Object Individuation in Infancy: Past and Present

Although object individuation was occasionally a topic of investigation in the early days of infancy research (Moore, Borton, & Darby, 1978), it was not until the 1990s that researchers began to explore systematically the development of this capacity (Spelke et al., 1995; Wilcox, 1999; Wilcox & Baillargeon, 1998a, 1998b; Xu & Carey, 1996). Initially, researchers focused on the importance of spatiotemporal information to the individuation process (Spelke et al., 1995; Xu & Carey, 1996). Xu and Carey (1996) claimed that infants younger than about 12 months use *only* spatiotemporal information to individuate objects and argued that it is not until the onset of language that infants have the conceptual structure required to individuate objects using property or kind information. Subsequent research has revealed, however, that given the appropriate task, young prelinguistic infants (Wilcox, 1999; Wilcox & Baillargeon, 1998a, 1998b; Wilcox & Schweinle, 2002) and nonlinguistic monkeys (Munakata, Santos, Spelke, Hauser, & O'Reilly, 2001; Santos, Sulkowski, Spaegen, & Hauser, 2002; Uller, Carey, Hauser, & Xu, 1997) can use featural information to individuate objects.

More recently, researchers have turned their attention toward identifying the type of featural information to which infants are

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most sensitive. Object features can be grouped into two broad categories: those features that specify the three-dimensional form of an object and those that convey information about surface properties. Wilcox and her colleagues (Wilcox, 1999; Woods & Wilcox, 2006a) have systematically investigated infants' sensitivity to form (i.e., shape, size) and surface (i.e., pattern, color, luminance) features during the 1st year of life. Most of this research has been conducted with the narrow-screen task. In the narrow-screen task, infants are presented with a test event in which two featurally distinct objects (e.g., a green ball and a red ball) emerge successively on opposite sides of a screen that is either too narrow (narrow-screen event) or sufficiently wide (wide-screen event) to hide both objects simultaneously. If infants (a) perceive the different-features event as involving two separate and distinct objects and (b) recognize that both objects can fit behind the wide but not the narrow screen, then they should find the narrow- but not the wide-screen event unexpected. Hence, longer looking to narrow- than to wide-screen events is taken as evidence for object individuation. This interpretation has been supported by data obtained using other violation-of-expectation tasks (Wilcox & Baillargeon, 1998a; Wilcox & Chapa, 2002; Wilcox & Schweinle, 2002; for a review, see Wilcox, Schweinle, & Chapa, 2003, or Wilcox & Woods, in press) and search tasks (McCurry, Wilcox, & Woods, 2005).[1]

The results of studies conducted with the narrow-screen task have revealed that by 4.5 months, infants use form features, such as shape and size, as the basis for individuating objects. In contrast, it is not until later in the 1st year that infants use surface features. Of most interest to the present research is the development of infants' sensitivity to color information. In one series of experiments, Wilcox (1999) presented 7.5-, 9.5-, and 11.5-month-olds with a green ball–red ball test event with a wide or a narrow screen. The results indicated that only the 11.5-month-olds interpreted the event as involving two separate and distinct objects (i.e., looked reliably longer at the narrow- than the wide-screen test event). These findings are consistent with data obtained in studies of object segregation and identification (Needham, 1999; Tremoulet et al., 2001), where an advantage for form over surface information has also been observed.

The finding that infants fail to use color differences to individuate objects until the end of the 1st year is intriguing because by 4.5 months infants have relatively good color vision: They detect, categorize, and demonstrate memory for color information (Banks & Salapatek, 1981, 1983; Banks & Shannon, 1993; Bornstein, 1975; Bornstein, Kessen, & Weiskopf, 1976; Brown, 1990; Catherwood, Crassini, & Freiberg, 1989; Hayne, Rovee-Collier, & Perris, 1987; Moskowitz-Cook, 1979; Powers, Schneck, & Teller, 1981; Teller & Palmer, 1996). Why, then, do young infants fail to draw on color differences to individuate objects?

Explaining Infants' Greater Sensitivity to Form Than Color Information

There are probably several factors that contribute to infants' greater sensitivity to form information than color information. It is likely that the developmental hierarchy favoring form features reflects, at least to some extent, the nature of the developing visual system. Because color vision is initially quite poor (Adams, 1995; Adams & Courage, 1998; Adams, Courage, & Mercer, 1994; Teller, 1998), young infants have difficulty getting good information about color. In contrast, infants' sensitivity to areas of high contrast (Adams & Maurer, 1984; Stephens & Banks, 1987) and to motion-related information (Arterberry & Yonas, 2000; Kellman, 1984; Kellman & Short, 1987; Slater, Mattock, & Brown, 1990; Slater & Morison, 1985; Slater, Morison, Town, & Rose, 1985) presents even young infants with many opportunities to gather information about object form. However, visual maturation cannot fully explain the developmental hierarchy favoring form features. Infants are sensitive to color differences long before they use those differences to individuate objects.

Wilcox and her colleagues (Wilcox, 1999; Wilcox & Chapa, 2004; Wilcox et al., 2003) have suggested that the developmental hierarchy favoring form features reflects, to a greater extent, information processing biases. According to this hypothesis, when faced with an individuation problem, infants (who have limited information-processing resources) attend to those features that are intimately tied to objects, that are predictive, and that are stable over time. Form features specify the physical nature of objects: the space they occupy, their substance, and how they will move and interact with other objects. Form features are also important for interpreting physical events. For example, the size and shape of an object determine whether it can fit into a container or serve as a source of support for another object. In addition, the form of an object rarely changes or becomes altered, and even young infants expect object form to remain stable across time and situations (Bahrick, 1987; Gibson & Walker, 1984; Granrud, 1987; Meltzoff & Borton, 1979; Slater et al., 1990; Slater & Morison, 1985; Spelke, 1979). In contrast, color information has little predictive value. Although color features typically co-occur with other object properties that are meaningful, color information is not unambiguously linked to objects or relevant to understanding the way in which the physical world operates (e.g., the color of an object does not predict whether it will fit into a container or support another

[1] Although some researchers have questioned the extent to which the narrow-screen task assesses object individuation in infants, there is now substantial evidence using different paradigms (McCurry, Wilcox, & Woods, 2006; Wilcox, 1999; Wilcox & Baillargeon, 1998b; Wilcox & Schweinle, 2002) that infants as young as 4.5 months can use featural information to individuate objects and show prolonged looking to different-features narrow-screen events because they are puzzled to see two objects out of view behind the narrow screen. For example, in a study conducted by McCurry et al. (2005; data are also reported in Wilcox & Woods, in press), 5- to- 7-month-olds were shown an event in which a box (box–ball event) or a ball (ball–ball event) disappeared behind one edge of a narrow or a wide screen and a ball appeared at the other edge. The screen consisted of a wooden frame to which multiple layers of fringe were attached; infants could reach but not see through the screen. Infants were then allowed to search. The infants who viewed the box–ball event spent significantly more time reaching through the fringed screen than reaching for the visible ball. In contrast, the infants who viewed the ball–ball event spent more time reaching for the ball than reaching through the screen. Infants in the narrow- and wide-screen conditions performed the same. These results suggest that the infants who saw the box–ball event interpreted the event as involving two objects, one of which was hidden behind the screen at the end of the trial. In addition, even though the narrow-screen box–ball infants were puzzled as to how both objects could both have been hidden behind the screen, they still perceived the event as involving two objects and actively searched for the box at the end of the event sequence.

object). In addition, color information may be perceived by infants as unstable across viewing conditions. For example, young infants may not perceive color as constant across different lighting conditions (Dannemiller, 1989; Dannemiller & Hanko, 1987). Because of these factors, infants do not view color information as particularly salient when tracking objects across space and time.

Increasing Infants' Sensitivity to Color Information

One question this analysis raises is whether infants' greater sensitivity to shape information than to color information is static and impenetrable or whether infants can be induced to attend to color differences. What kinds of experiences might lead infants to attend to color information? One approach that Wilcox and her colleagues (Wilcox, 2004; Wilcox & Chapa, 2004) have taken is to make color functionally relevant. In one set of studies, Wilcox and Chapa (2004) presented 9.5-month-olds with events, prior to an individuation task, in which the color of an object predicted the function in which it would engage. In the first pair of pretest events, infants saw a green can with a handle pound a peg; they then saw a red can with a handle pour salt. The cans were identical except for their color. In the second pair of pretest events, the green and red cans were replaced with green and red cups. Immediately following the pound–pour events, infants were shown the green ball–red ball test event with the narrow or the wide screen. After viewing the pound–pour events, the 9.5-month-olds looked reliably longer at the narrow- than the wide-screen test event, indicating that they had used the color difference to individuate the balls. Recall that 9.5-month-olds do not typically use color information as the basis for individuating objects. Subsequent studies revealed that it is the linking of color information to object function (an object property to which infants are particularly sensitive), and not other aspects of the pretest events, that primes[2] infants to attend to the color difference in the individuation task.

The hypothesis that infants can be led, through select experiences, to attend to information to which they typically do not attend also has been tested by Wang and Baillargeon (2005) in another physical domain. Research indicates that by 3.5 months, infants attend to height information when interpreting occlusion events (Baillargeon & DeVos, 1991; Baillargeon & Graber, 1987) but that it is not until about 12 months that infants attend to height when interpreting uncovering events (Wang, Baillargeon, & Paterson, 2005). An occlusion event is when an object moves behind a nearer object or surface, whereas a covering event is when a cloth or cover is placed over an object. Wang and Baillargeon (2005) examined whether infants could be led to attend to height in an uncovering event if the object involved was first seen in an occlusion event. In one experiment, 8-month-olds saw a pretest event in which a cylinder was placed in front of an object until the object became fully occluded. Next, infants saw a test event in which the cylinder was placed over the object until the object was fully covered. For half the infants, the cylinder used in the occlusion and covering sequence was taller than the object (tall-cylinder condition); for the other infants, the cylinder was much shorter than the object (short-cylinder condition). The infants in the short-cylinder condition looked reliably longer during the covering sequence than did the infants in the tall-cylinder condition, a finding suggesting that the infants recognized that the tall cylinder but not the short one was sufficiently tall to cover the object. These results, along with those obtained in a control condition in which the pretest event did not involve occlusion, suggest that viewing an event in which height has already been identified as a relevant variable can lead infants to attend to height information in an event in which they typically do not attend to height information. Although the mechanism responsible for infants' increased sensitivity to height information in the study by Wang and Baillargeon (2005) is probably different from that responsible for infants' increased sensitivity to color information in the study by Wilcox and Chapa (2004), these results provide converging evidence for the idea that infants' object representations are flexible and can be altered by recent experiences.

Given this flexibility, there might be other means by which infants can be induced to attend to color information. The priming experiments discussed above relied on infants' propensity to take information to which they were already sensitive and use that information to make sense of other, less salient forms of information. In the pound–pour experiments, successful priming depended on infants' capacity to detect regularities across visual events. Infants demonstrated increased sensitivity to color information when they detected the link between color and function: when they recognized that the color of an object predicted the function in which it would engage. Once color became predictive, or functionally relevant, infants were more likely to attend to color differences in the individuation task. Although this type of priming is very effective, it may not be the only type of priming that can facilitate infants' use of color information. There may be other mechanisms by which infants can be led to view color as a relevant object property.

Once infants can sit up unsupported and begin to reach for and actively manipulate objects, around 5 months of age (Rochat, 1989; Rochat & Goubet, 1995; Streri, 1991/1993), simultaneous visual and tactile exploration is one of the most common mechanisms for learning about objects. Visual and tactile exploration provides infants with the opportunity to experience the same information in more than one modality (e.g., shape encoded tactilely and visually) as well as to link information from one modality to another (e.g., to link color encoded visually to shape encoded tactilely). How might visual and tactile exploration draw infants' attention to color information? How might multimodal processing facilitate infants' use of color information in an object individuation task? In their day-to-day lives, infants typically encounter multimodal events, in which they are presented with both amodal (i.e., experienced by two or more senses) and modality-specific (i.e., experienced by a single sense) information about objects. Some researchers have proposed that information available concurrently to two or more senses, because it is invariant and redundant, is highly salient to infants; it captures attention and directs exploration (Bahrick & Lickliter, 2002; Bahrick, Lickliter, & Flom, 2004; Lickliter & Bahrick, 2002; Slater, Quinn, Brown, & Hayes, 1999). This promotes learning about regularities in the environment and focuses infants' attention on meaningful object properties. There is a substantial body of literature demonstrating that infants are excellent perceivers of amodal information

[2] We use *priming* as a general term defined by cognitive scientists as "the enhancement of the processing of a stimulus as a function of prior exposure" (Anderson, 2005).

and are highly skilled at forming object percepts that include amodal object properties (see Bahrick, 2004, for a review). In contrast, infants are less likely to attend to and use modality-specific information. Because modality-specific information, such as color, is experienced in only a single modality, and because it often lacks predictability and is not intimately linked to objects, infants view modality-specific information as less salient. It is not that infants cannot perceive modality-specific information, but they have difficulty establishing the relation of these properties to other object properties and understanding how modality-specific information might be relevant to interpreting physical events.

Bahrick and her colleagues (Bahrick & Lickliter, 2000, 2002; Bahrick et al., 2004; Bahrick & Pickens, 1994; Lickliter & Bahrick, 2002) have articulated a comprehensive model of intermodal processing that focuses on the importance of detecting amodal relations within the context of multimodal events. Two components of this model are particularly relevant to the present research. First, amodal relations are detected prior to modality-specific relations. That is, when exploring and interacting with objects, infants attend first to amodal properties and then to modality-specific properties. Second, the detection of amodal relations guides and constrains learning about arbitrary relations. That is, the extent to which infants attend to modality-specific information depends on whether they have formed an amodal representation. Note that amodal information can be experienced unimodally (e.g., shape experienced visually) or multimodally (e.g., shape experienced visually and tactilely). Amodal representations are formed only when amodal information is experienced in two or more senses concurrently. The outcomes of a number of studies support this proposal. For example, by 3 months, infants recognize that the sound an object makes when striking a surface is related to its visual features (e.g., an object composed of a single item makes a different sound than an object composed of multiple items). However, it is not until 7 months that infants detect the arbitrary relation between an impact sound and the color of an object (Bahrick, 1992, 1994). Likewise, very young infants can detect the relation between shape experienced tactilely and shape experienced visually, but they have difficulty detecting the arbitrary relation between tactilely experienced shape and visually experienced color or pattern (Hernandez-Reif & Bahrick, 2001). However, when shape is made available tactilely and visually, so that amodal information about shape unifies infants' experiences across the senses, infants can learn the relation between an object's color or pattern and its shape.

Current Research

The results obtained by Bahrick and her colleagues (Bahrick & Lickliter, 2000, 2002; Bahrick et al., 2004; Bahrick & Pickens, 1994; Lickliter & Bahrick, 2002) make a straightforward prediction about how we might facilitate infants' use of color information as the basis for individuating objects. Recall that in the narrow-screen task, the objects are experienced only visually. Perhaps if infants were allowed multisensory exploration of the test objects, so that they could form amodal representations, they would be more likely to attend to color information. To test this hypothesis, we examined the extent to which simultaneous visual and tactile exploration of objects increases infants' sensitivity to color differences in a subsequent individuation task. Previous research indicates that 11.5-month-olds, but not 9.5-month-olds, spontaneously use color information to individuate objects (Wilcox, 1999). To determine the best age at which to implement a multisensory exploration procedure, we first assessed 10.5-month-olds' sensitivity to color information. The outcome of this experiment indicated that 10.5-month-olds, like 9.5-month-olds, failed to use a color difference to individuate the objects. The remaining experiments assessed the conditions under which 10.5-month-olds could be primed, through visual and tactile exploration of objects, to attend to color differences in an individuation task. In addition, the effectiveness of the multisensory exploration procedure with younger infants was explored.

Experiment 1

Experiment 1 assessed 10.5-month-olds' capacity to use color information to individuate objects using the narrow-screen task. We chose to use the narrow-screen task so that we could directly compare the outcome of the present studies with studies in which infants failed to use color differences to individuate objects (Wilcox, 1999) or in which infants were primed by other experiences to attend to color differences (Wilcox & Chapa, 2004). Infants participated in a two-phase procedure that consisted of a familiarization phase and a test phase. In the *familiarization phase*, infants were presented with a familiarization event in which a green ball and a red ball emerged successively on opposite sides of a wide yellow screen. The two objects moved in the same depth plane (i.e., along the same axis), so that it would not have been possible for them to pass each other behind the screen without colliding. The purpose of the familiarization trials was to acquaint the infants with the objects they would see in the test trials. In the *test phase*, infants were presented with a test event (see Figure 1) that was identical to the familiarization event except that the yellow screen was replaced with a blue screen that was either sufficiently wide (wide-screen condition) or too narrow (narrow-screen condition) to hide both objects simultaneously. If infants (a) perceive the green ball–red ball event as involving two separate and distinct objects and (b) recognize that both objects can fit behind the wide screen but not the narrow screen, then they should find the narrow- but not the wide-screen event unexpected (i.e., they should look reliably longer at the narrow- than the wide-screen test event). In contrast, if infants fail to use the color difference to individuate the objects, then they should not find the narrow-screen event unexpected (i.e., they should look equally at the narrow- and wide-screen test events).

Method

Participants

Participants were 16 healthy full-term infants, 8 male and 8 female (mean age = 10 months, 14 days; range = 10 months, 0 days to 10 months, 29 days) recruited from a university community in the southwest. Parents reported their infants' race/ethnicity as Caucasian ($n = 12$), Hispanic ($n = 3$), or Black ($n = 1$). In this and the following experiments, information about parents' socioeconomic status, educational level, and income was not available. One additional infant was tested but eliminated because of a family

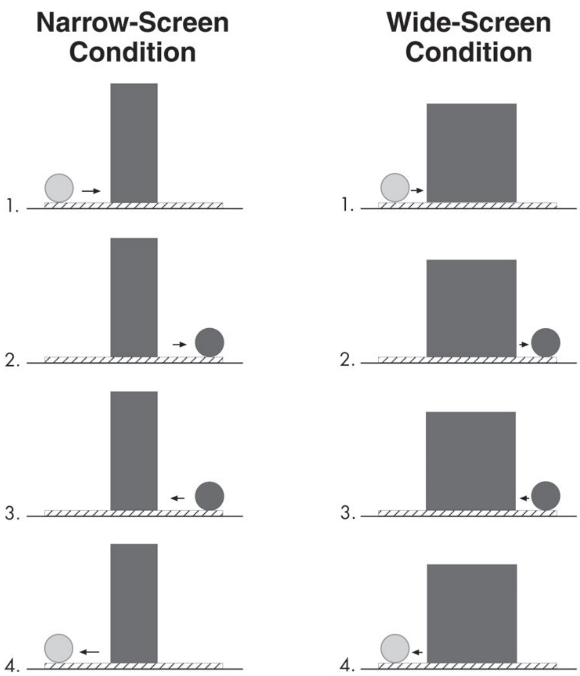

Figure 1. Schematic drawing of the test events in the narrow- and wide-screen conditions of Experiments 1 through 5A. The ball to the left of the screen was green, and the ball to the right was red.

history of color blindness.[3] Eight infants were randomly assigned to each of two conditions (narrow or wide screen). In this and all subsequent experiments, the infants' names were obtained from multiple sources, including birth announcements in the local newspaper and commercially produced lists.

Apparatus

The apparatus consisted of a wooden cubicle 213 cm high, 105 cm wide, and 43.5 cm deep. The infant sat facing an opening 51 cm high and 93 cm wide in the front wall of the apparatus. The floor and walls of the apparatus were cream colored or covered with lightly patterned contact paper. A platform 1.5 cm high, 60 cm wide, and 19 cm deep lay at the back wall and was centered between the left and right walls.

The balls used in the familiarization and test events were 10.25 cm in diameter and made of Styrofoam. One ball was painted green and approximated the hue of 2.5G 5/10 of the Munsell matte collection (Munsell, 2005). The other ball was painted red and approximated the hue of 5R 4/14. The balls were of equal luminance (35 cd/m^2). Each ball was attached to a clear Plexiglas base, and each base had a 16-cm handle that protruded through a small gap between the back wall and floor of the apparatus; the gap was masked by cream-colored fringe. An experimenter, concealed behind the apparatus, could move the balls left and right along the platform using the Plexiglas handle.

The screen used in the familiarization trials was 41 cm high and 30 cm wide and made of yellow cardboard. The narrow test screen was 41 cm high and 17 cm wide, and the wide test screen was 33 cm high and 30 cm wide. Hence the narrow test screen differed from the familiarization screen in width, and the wide screen differed from the familiarization screen in height (i.e., each test screen varied from the familiarization screen on one dimension). The test screens were made of blue cardboard and decorated with small gold and silver stars. The screens were mounted on a wooden stand that was centered in front of the platform.

Embedded in the center of the platform was a metal bilevel mechanism composed of an upper shelf and a lower shelf 16 cm apart; each shelf was 12.7 cm wide and 13 cm deep. The bi-level design ensured that both objects could be behind the screen simultaneously, one on the top shelf and the other on the bottom shelf. When at rest, the upper shelf was level with the top of the platform and the lower shelf lay underneath the apparatus floor. The bi-level mechanism could be lifted by means of a handle 19 cm long that protruded through a vertical opening in the apparatus's back wall; when the bi-level mechanism was lifted, its lower shelf became level with the platform. The bi-level mechanism remained hidden behind the screen in its raised position.

A muslin-covered shade was lowered in front of the opening in the front wall of the apparatus at the end of each trial. Two muslin-covered wooden frames, each 213 cm high and 68 cm wide, stood at an angle on either side of the apparatus and isolated the infants from the experimental room. In addition to the room lighting, a 20-watt fluorescent bulb was affixed to each inside wall of the apparatus.

Events

Each experimental session included familiarization and test events. One experimenter produced all of the events. The experimenter wore a white glove on her right hand and followed a precise script, using a metronome that ticked softly once per second. The numbers in parentheses in the following paragraphs indicate the time taken to produce the actions described. The experimenter moved the objects by their handles from behind the apparatus, so no part of her was visible to the infant.

Narrow-screen condition. Each infant saw a familiarization event. At the start of each familiarization trial, the green ball sat with its center 6 cm from the left end of the platform. The familiarization screen stood upright and centered in front of the platform, and the red ball sat on the lower shelf of the bi-level mechanism.

Each familiarization trial began with a brief pretrial. When the computer signaled that the infant had looked for 1 cumulative second, the ball paused for 1 more second and then moved to the right until it reached the upper shelf of the bi-level mechanism behind the screen (2 s), so that the handle of the ball's base aligned with the handle of the bi-level mechanism. Next, the bi-level mechanism was lifted until its lower shelf was level with the platform (1 s); the red ball then emerged from behind the screen and moved to the right until its center was 6 cm from the right end of the platform (2 s). After a 1-s pause, the red ball returned to the

[3] In Experiments 1 through 5A and 5B, parents were asked to report family history of color blindness. Male infants were eliminated from analysis if color blindness was reported for a member of the mother's immediate family. Female infants were eliminated from analysis if color blindness was reported for a member of the mother's immediate family and if the biological father was reported as color blind.

bi-level mechanism (2 s), which was lowered (1 s) until its upper shelf was once again even with the platform; the green ball then returned to its starting position at the left end of the platform (2 s). When in motion, the balls moved at a rate of 12 cm per s. The 12-s event sequence just described was repeated continuously until the trial ended.

Next, the infants saw a test event. The test event was identical to the familiarization event except that the familiarization screen was replaced with the narrow test screen.

Wide-screen condition. The familiarization and test events were identical to those in the narrow-screen condition with one exception: In the test event, the narrow screen was replaced with the wide screen.

Procedure

Each infant sat on a parent's lap centered in front of the apparatus, approximately 78 cm from the objects on the platform. Parents were asked not to interact with their infants while the experiment was in progress and to close their eyes during the familiarization and test trials.

The infants participated in a two-phase procedure that consisted of a familiarization phase and a test phase. During the familiarization phase, the infants saw the familiarization event appropriate for their condition on six successive trials. Each trial ended 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 two successive trials. Each trial ended when the infant (a) looked away for 2 consecutive seconds after having looked at the event 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 observers who watched the infant through peepholes in the cloth-covered frames on either side of the apparatus. The observers were not told, and could not determine, whether infants saw a narrow- or a wide-screen test event.[4] Each observer held a button connected to a computer and depressed the button when the infant attended to the events. The looking times recorded by the primary observer determined when a trial had ended and were used in the data analyses. Each trial was divided into 100-ms intervals, and the computer determined in each interval whether the two observers agreed on the direction of the infant's gaze. Interobserver agreement was measured for 15 of the infants (for 1 of the infants, only one observer was present) and was calculated for each test trial on the basis of the number of intervals in which the computer registered agreement out of the total number of intervals in the trial. Agreement averaged 92% per test trial per infant.

Preliminary analyses were conducted for each of the experiments reported herein to explore whether male and female infants responded differently to the test events. These analyses failed to reveal reliable sex differences. Consequently, in this and the following experiments, the data were collapsed across sex.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model analysis of variance (ANOVA) with trial as the within-subject factor and condition (narrow or wide screen) as the between-subjects factor. The main effect of trial was significant, $F(5, 70) = 9.44$, $p < .001$, $\eta_p^2 = .56$, indicating that looking times decreased significantly across familiarization trials. To illustrate, the infants' looking times averaged across Trials 1 and 2 ($M = 39.4$ s, $SD = 13.3$) were greater in magnitude than those averaged across Trials 3 and 4 ($M = 25.1$ s, $SD = 7.1$) and Trials 5 and 6 ($M = 19.5$ s, $SD = 7.7$). The main effect of condition was not significant, $F(1, 14) < 1$, nor was the Trial $\times$ Condition interaction, $F(5, 70) < 1$. The infants in the narrow-screen ($M = 27.1$ s, $SD = 4.1$) and wide-screen ($M = 29.0$ s, $SD = 7.9$) conditions looked about equally at the familiarization event.

Test Trials

The infants' looking times during the two test trials (see Figure 2) were analyzed in the same manner as the familiarization trials. The main effect of trial was not significant, $F(1, 14) = 2.65$, $p > .05$. The main effect of condition was not significant, $F(1, 14) < 1$, nor was the Trial $\times$ Condition interaction, $F(1, 14) = 3.30$, $p > .05$. The infants in the narrow-screen ($M = 18.3$ s, $SD = 10.0$) and the wide-screen ($M = 19.5$ s, $SD = 11.4$) conditions looked about equally at the test event, as if they failed to use the difference in color between the green ball and the red ball to draw inferences about the number of objects involved in the occlusion sequence. These results suggest that 10.5-month-olds, like 9.5-month-olds, do not spontaneously use color differences to individuate objects.

The outcome of Experiment 1 led us to begin our investigations with 10.5-month-olds. The next experiment examined the extent to which 10.5-month-olds' sensitivity to color information could be increased through multisensory exploration of the balls.

Experiment 2

There is substantial evidence that multimodal experiences lead infants to form object representations that are more rich and robust than those formed during unimodal experiences (Bahrick & Lickliter, 2000, 2002; Bahrick et al., 2004; Lickliter & Bahrick, 2002; Slater et al., 1999). Most relevant to the present research is the finding that multisensory exploration of objects, in which amodal properties can be experienced concurrently in at least two different modalities, enhances infants' capacity to attend to modality-specific information, such as color, in object processing tasks (Bahrick, 1992, 1994; Hernandez-Reif & Bahrick, 2001). On the basis of these findings, we hypothesized that simultaneous visual and tactile exploration of the test objects, prior to the individuation

[4] In Experiments 1 through 5A and 5B, infants saw the green ball–red ball test event with a narrow or a wide screen. Observers were asked to guess, at the end of each session, whether the infant saw a narrow- or a wide-screen test event. Of the 104 primary observers who responded, 54 guessed correctly, a performance not significantly different from chance (cumulative binomial probability, $p > .05$).

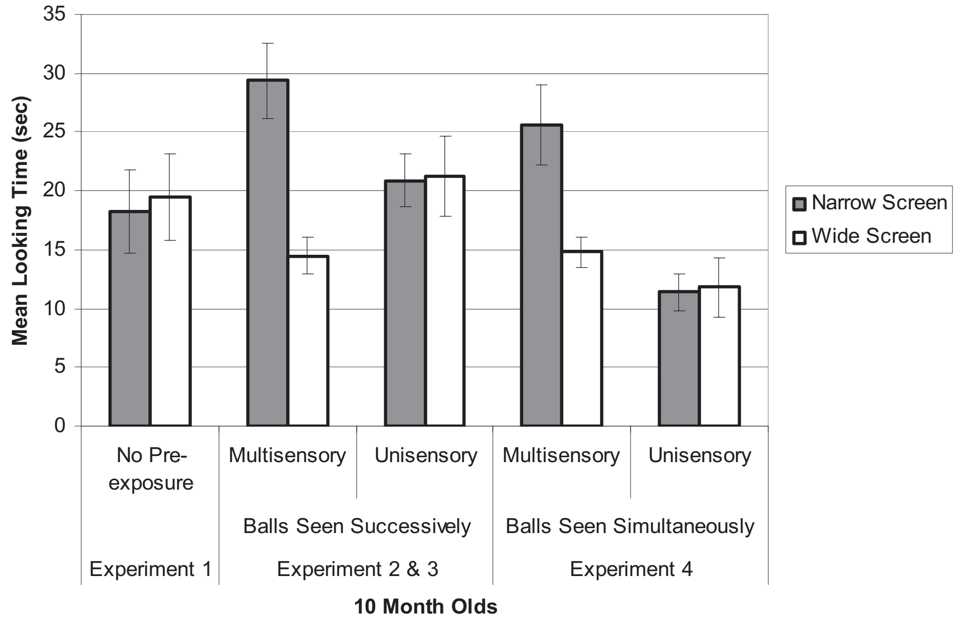

Figure 2. Mean looking times (in seconds) of the 10.5-month-old infants in Experiments 1 through 4 to the test events. Vertical lines depict standard errors of the means.

task, would increase the likelihood that infants would attend to the color of those objects and then use the color difference as the basis for individuation. To test this hypothesis, we allowed infants aged 10.5 months to look at and manually explore the green ball and the red ball, one at a time, prior to the familiarization and test events.

Method

Participants

Participants were 16 healthy full-term infants, 8 male and 8 female (mean age = 10 months, 13 days; range = 10 months, 2 days to 10 months, 24 days). Parents reported their infants' race/ethnicity as Caucasian (n = 13), Hispanic (n = 2), or mixed race of Asian and Caucasian (n = 1). Seven additional infants were tested but eliminated because of fussiness (n = 3), a family history of color blindness (n = 1), procedural problems (n = 1), sustained attention (i.e., the infant looked 60 s on all familiarization and test trials; n = 1), or because the primary observer was unable to determine the infant's direction of gaze (n = 1). Eight infants were randomly assigned to each of two conditions (narrow or wide screen).

Apparatus and Test Events

The apparatus and test events were identical to those of Experiment 1.

Procedure

The procedure was identical to that of Experiment 1 with one exception: Prior to the individuation task, infants were given two 60-s preexposure trials that took place in a room separate from that where familiarization and test trials took place. Infants sat on the parent's lap or on the floor near the parent. In the first preexposure trial, the experimenter handed the infant the green ball and encouraged the infant to look at and touch the ball. If the infant was unwilling to accept the ball from the experimenter, the experimenter handed the ball to the parent, who then handed it to the infant. If the infant dropped, threw, or rolled the ball out of his or her reach, the experimenter retrieved the ball and returned it to the infant. The second preexposure trial was identical to the first except that the infant was presented with the red ball. The balls were presented successively, never together. Parents were instructed not to label the balls or refer to their colors during the preexposure or the test trials.

Following the two preexposure trials, infants were escorted to the testing room, where they saw the green ball–red ball test event with the narrow or the wide screen. Interobserver agreement during the test trials was measured for 11 of the infants and averaged 91% per test trial per infant.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model ANOVA with trial as the within-subject factor and condition (narrow or wide screen) as the between-subjects factor. The main effect of trial was significant, $F(5, 70) = 23.49$, $p < .001$, $\eta_p^2 = .63$, indicating that looking times decreased significantly across familiarization trials. To illustrate, the infants' looking times averaged across Trials 1 and 2 (M = 42.7 s, SD = 9.9) were greater in magnitude than those averaged across Trials 3 and 4 (M = 24.4 s, SD = 7.8) and Trials 5 and 6 (M = 19.2 s, SD = 6.8). The main effect of condition was not significant, $F(1, 14) < 1.75$, nor was the Trial × Condition interaction, $F(5, 70) < 1.75$. The infants in the narrow-screen ($M = 29.3$ s, $SD = 6.5$) and the wide-screen ($M = 27.8$ s, $SD = 6.6$) conditions looked about equally during the familiarization trials.

Test Trials

The infants' looking times during the two test trials (see Figure 2) were analyzed in the same manner as the familiarization trials. The main effect of trial was not significant, $F(1, 14) = 4.55$, $p > .05$. The main effect of condition was significant, $F(1, 14) = 14.77$, $p = .002$, $\eta_p^2 = .51$, but the Trial × Condition interaction was not, $F(1, 14) < 2$, indicating that the infants in the narrow-screen condition ($M = 29.4$ s, $SD = 9.0$) looked reliably longer during the test trials than the infants in the wide-screen condition ($M = 14.5$ s, $SD = 4.5$). These results stand in contrast to those obtained in Experiment 1, where the infants looked about equally at the narrow- and the wide-screen test events.

Additional Results

After visual and tactile exploration of the green and the red balls, the infants looked reliably longer at the narrow-screen than the wide-screen event, suggesting that they used the color difference to individuate the balls in the test event. However, there is an alternative, weaker interpretation of the data that should be considered. It is possible that two manual presentations of the balls led the infants to conclude that two physically distinct balls were present. That is, perhaps the experience of tactilely encountering the balls on two separate occasions (i.e., two trials) was sufficient to signal the presence of two objects. According to this interpretation, the number of times the balls were manually presented to the infants, and not increased sensitivity to color information, led infants to individuate the balls.

To assess this weaker interpretation, we tested an additional group of 10.5-month-olds ($N = 8$, mean age = 10 months, 13 days) using the multisensory exploration procedure of Experiment 2 but with one important difference: We presented the infants with the same ball on both preexposure trials. One half of the infants were presented with the green ball twice, and the other half were presented with the red ball twice. All infants saw the narrow-screen test event. If the multisensory exploration procedure facilitates performance on the individuation task because two manual presentations signal the presence of two objects, then the infants in the control condition should successfully individuate the balls in the test event. In contrast, if the multisensory exploration procedure facilitates performance on the individuation task because it leads infants to attend to the difference in color between the balls, then the infants in the control condition should fail to individuate the balls in the test event.

The data obtained from the infants in the control narrow-screen condition were compared with those obtained from the infants in the experimental (i.e., multisensory) narrow- and wide-screen conditions using a one-way ANOVA with condition (narrow-screen, wide-screen, control narrow-screen) as the between-subjects factor. (Because the main analyses revealed no main effects or interactions involving trial, familiarization and test data were averaged across trials.) Analysis of the familiarization data revealed no significant effect of condition, $F(1, 21) = 2.38$, $p > .05$ (control narrow-screen, $M = 23.4$ s, $SD = 2.8$), indicating that the infants in the three conditions looked about equally during the familiarization trials. Analysis of the test data revealed a significant effect of condition, $F(1, 21) = 9.28$, $p = .001$, $\eta_p^2 = .47$. Planned comparisons indicated that the looking times of the infants in the control narrow-screen condition ($M = 16.4$ s, $SD = 8.4$) differed reliably from those of the infants in the narrow-screen condition, $F(1, 21) = 21.2$, $p < .001$, Cohen's $d = 1.49$, but not from those of the infants in the wide-screen condition, $F(1, 21) < 1$. The fact that the infants in the control narrow-screen condition did not demonstrate prolonged looking to the test event suggests that they failed to use the color difference to individuate the green and the red balls. Seeing the same-colored ball on both preexposure trials did not induce infants to attend to the color difference in the narrow-screen test event. This outcome supports the conclusion that the multisensory exploration procedure facilitates test performance because it increases infants' sensitivity to color information and not because two manual presentations of the balls signalled the presence of two distinct objects.

What is it about the multisensory experience that leads infants to attend to color information? We have suggested that the experience of looking at and touching the ball, simultaneously, leads infants to form an amodal representation. Once an amodal representation is formed, infants can then attend to the surface features of the ball. This experience facilitates infants' use of color information in the subsequent test event. However, there is an alternative interpretation of the data. Perhaps infants are slow to process color information, and additional exposure to each ball provides the extra time required to encode color. According to this hypothesis, it is not combined visual and tactile experience but additional visual encoding that increases infants' sensitivity to color information. Experiment 3 tested this hypothesis.

Experiment 3

The infants in Experiment 3 were tested using the procedure of Experiment 2 but with one important difference: They were allowed to look at but not touch the balls during the preexposure trials.

Method

Participants

Participants were 16 healthy full-term infants, 8 male and 8 female (mean age = 10 months, 19 days; range = 10 months, 2 days to 10 months, 29 days). Parents reported race/ethnicity as Caucasian ($n = 13$), Black ($n = 2$), or mixed race of Asian and Caucasian ($n = 1$). Two additional infants were tested but eliminated because of procedural problems. Eight infants were randomly assigned to each of two conditions (narrow or wide screen).

Apparatus and Test Events

The apparatus and test events were identical to those of Experiment 2.

Procedure

The procedure was identical to that of Experiment 2 with one exception: Rather than hand the ball to the infant, the experimenter held the ball in the palm of her hand directly in front of the infant, just out of arms' reach.

Following the two preexposure trials, infants were again escorted to the testing room where they saw the green ball–red ball test event with the narrow or the wide screen. Interobserver agreement during the test trials was measured for 14 of the infants and averaged 90%.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model ANOVA with trial as the within-subject factor and condition (narrow or wide screen) as the between-subjects factor. The main effect of trial was significant, $F(5, 70) = 11.71$, $p < .001$, $\eta_p^2 = .46$, indicating that looking times decreased significantly across familiarization trials. The infants' looking times averaged across Trials 1 and 2 (M = 42.6 s, SD = 12.5) were greater in magnitude than those averaged across Trials 3 and 4 (M = 30.6 s, SD = 9.9) and Trials 5 and 6 (M = 21.2 s, SD = 5.9). The main effect of condition was not significant, $F(1, 14) < 1$, nor was the Trial × Condition interaction, $F(5, 70) < 1$. The infants in the narrow-screen (M = 33.9 s, SD = 7.3) and the wide-screen (M = 29.9 s, SD = 7.7) conditions looked about equally during the familiarization trials.

Test Trials

The infants' looking times during the two test trials (see Figure 2) were analyzed in the same manner as the familiarization trials. The main effect of trial was not significant, $F(1, 14) < 1.75$. The main effect of condition and the Trial × Condition interaction were not significant, $Fs(1, 14) < 1$.

The infants in the narrow-screen (M = 20.9 s, SD = 6.6) and the wide-screen (M = 21.3 s, SD = 9.7) conditions looked about equally during the test trials.

The test data obtained in Experiment 3 were also analyzed together with those obtained in Experiment 2 by means of a one-way ANOVA with exploration type (multisensory or unisensory) and event (narrow or wide screen) as between-subjects factors. There were no significant main effects or interactions involving trial in Experiments 2 and 3; hence data were collapsed across this factor. The analysis revealed a significant interaction between exploration type and event, $F(1, 28) = 7.89$, $p < .01$, $\eta_p^2 = .22$. Planned comparisons indicated that the infants who had multisensory experience looked reliably longer at the narrow- than at the wide-screen test event, $F(1, 28) = 7.89$, $p < .01$, Cohen's $d = 2.09$, whereas the infants who had unisensory experience looked about equally at the two events, $F(1, 28) < 1$. In addition, the infants who had multisensory experience looked reliably longer at the narrow-screen test event than did the infants who had unisensory experience, $F(1, 28) = 4.86$, $p < .05$, Cohen's d = 1.08.

One might be concerned that the infants in the multisensory condition spent more time looking at the balls during the preexposure trials than did the infants in the unisensory condition. Perhaps touching the balls focused infants' visual attention on the balls, and it was this additional encoding time rather than the type of encoding (multisensory vs. unisensory) that led to different patterns of performance in the test trials. To assess this interpretation of the data, we had two independent observers watch the videotapes and code the amount of time infants spent looking at the ball during each preexposure trial. Unfortunately, videotapes were unavailable for some infants. The final samples were $N = 10$ (of 16) for Experiment 2 and $N = 15$ (of 16) for Experiment 3. Interobserver agreement was calculated for infants' looking times and averaged 93% per trial per infant. Infants' looking times were then averaged across the two preexposure trials and compared by means of a t test with exploration type (multisensory or unisensory) as the independent variable. The effect of exploration type was not significant, $t(23) < 1$, indicating that the infants in the multisensory exploration condition (M = 52.7 s, SD = 26.5) did not differ reliably in the amount of time they spent looking at the balls during the preexposure trials from the infants in the unisensory exploration condition (M = 52.0 s, SD = 15.0).

Together, the results reported here suggest that combined visual and tactile exploration of the objects, but not visual exploration alone, increased infants' sensitivity to color information in the test trials. It is not additional encoding time per se, but the kind of encoding that occurs during multisensory exploration, that facilitates infants' attention to color information in the subsequent test event.

The outcomes of Experiments 2 and 3, collectively, are striking. Although we had reason to suspect that combined visual and tactile exploration would enhance infants' attention to color information, this is the first demonstration that engaging in manual manipulation of objects is more effective in facilitating the individuation process than visual examination alone. Given the importance of these findings to models of object individuation, and to an understanding of the functional distinction between multimodal and unimodal processing, we examined further the role of multisensory and unisensory exploration to the priming process.

Experiment 4

In Experiment 4, we addressed the question of whether under more supportive conditions, visual exploration alone might facilitate infants' sensitivity to color information. Perhaps if the task of establishing distinct object representations was made easier for the infants, by giving them clear spatiotemporal information about the number of balls present in the preexposure trials, they would be more likely to attend to color information.

To assess this hypothesis, we tested 10.5-month-olds by using the multisensory exploration procedure of Experiment 2, or the unisensory exploration procedure of Experiment 3, with one important difference: In the preexposure trials, the green ball and the red ball were presented together, side by side. Hence, infants were given spatiotemporal information that two objects—a green ball and a red ball—were present in the preexposure trials. If the spatiotemporal information leads infants to establish two object representations and then attend to the color difference, the infants in both conditions should look reliably longer at the narrow-screen than the wide-screen test event. In contrast, if multisensory exploration is necessary in order for infants to attend to color information, even when the objects can be individuated on the basis of spatiotemporal discontinuities, only the infants in the multisensory exploration condition should look reliably longer at the narrow-screen than the wide-screen test event.

Method

Participants

Participants were 28 healthy full-term infants, 16 male and 12 female (mean age = 10 months, 16 days; range = 10 months, 2 days to 10 months, 29 days). Parents reported race/ethnicity as Caucasian (n =23), Hispanic (n = 4), or Asian (n = 1). Five additional infants were tested but eliminated because they refused to touch the ball during the preexposure trials (n = 1), because the parent labeled the ball during the preexposure or test trials (n = 3), or because of procedural problems (n = 1). Seven infants were randomly assigned to each of four conditions formed by crossing exploration type (multisensory or unisensory) and test event (narrow or wide screen).

Apparatus and Test Events

The apparatus and test events were identical to those of Experiments 2 and 3.

Procedure

The multisensory and unisensory procedures were identical to those of Experiments 2 and 3 with one exception: During each preexposure trial, infants were presented with the green ball and the red ball simultaneously. For the first preexposure trial, the green ball was presented in the experimenter's right hand, and the red ball was presented in her left hand. The two hands were equidistant from the infant and separated from each other by a gap of approximately 2 cm. In the multisensory condition, the infants were allowed to look at and manipulate both balls simultaneously. In the unisensory condition, the infants were allowed only to look at the balls. For the second preexposure trial, the position of the balls was reversed. Interobserver agreement was measured for 27 of the infants and averaged 91%.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model ANOVA with trial as the within-subject factor and exploration type (multisensory or unisensory) and test event (narrow or wide screen) as between-subjects factors. The main effect of trial was significant, $F(5, 120) = 46.07$, $p < .001$, $\eta_p^2 = .66$, indicating that looking times decreased significantly across familiarization trials. The infants' looking times averaged across Trials 1 and 2 (M = 42.9 s, SD = 11.8) were greater in magnitude than those averaged across Trials 3 and 4 (M = 22.3 s, SD = 7.0) and Trials 5 and 6 (M = 18.9 s, SD = 5.4). The main effect of exploration type was also significant, $F(1, 24) = 6.41$, $p < .025$, $\eta_p^2 = .21$. The main effect of test event and the Exploration Type × Test Event interaction were not significant, Fs(1, 24) < 1.5. In addition, none of the interactions involving trial was significant, Fs(5, 120) < 2.25. Together, these results suggest that the infants in the multisensory exploration condition looked reliably longer during the familiarization trials than did the infants in the unisensory exploration condition but that looking times did not vary by whether the infants would see a narrow- or a wide-screen test event (multisensory exploration, narrow screen, M = 28.9 s, SD = 4.1, and wide screen, M = 30.6 s, SD = 5.5; unisensory exploration, narrow screen, M = 26.2 s, SD = 7.0, and wide screen, M = 24.5 s, SD = 6.0). All interactions involving trial, Fs(5, 120) < 2.25, were not significant.

Test Trials

The infants' looking times during the two test trials (see Figure 2) were analyzed in the same manner as the familiarization trials. The main effect of trial, $F(1, 24) = 2.65$, $p > .05$, was not significant. The main effect of exploration type, $F(1, 24) = 12.98$, $p = .01$, $\eta_p^2 = .35$, the main effect of test event, $F(1, 24) = 4.79$, $p < .05$, $\eta_p^2 = .17$, and the Exploration Type × Test Event interaction, $F(1, 24) = 5.34$, $p = .05$, $\eta_p^2 = .18$, were significant. All interactions involving trial were not significant, Fs(1, 24) < 1. Planned contrasts indicated that the infants in the multisensory exploration condition looked reliably longer at the narrow-screen (M = 25.6 s, SD = 9.1) than at the wide-screen (M = 14.8 s, SD = 3.5) test event, $F(1, 24) = 10.23$, $p < .01$, Cohen's d = 1.57. In contrast, the infants in the unisensory exploration condition looked about equally at the narrow-screen (M = 11.4 s, SD = 4.3) and the wide-screen (M = 11.8 s, SD = 6.7) test events, $F(1, 24) < 1$. These results suggest that only the infants in the multisensory condition individuated the balls in the test event.

Given that the analysis of the familiarization data yielded a significant main effect of exploration type, the test data were subjected to an analysis of covariance (ANCOVA); the factors were the same as in the ANOVA except that trial was excluded as a factor, and the covariate was the infants' mean familiarization looking times. The purpose of this analysis was to determine whether the same test results would obtain after adjusting for the difference in familiarization looking times between the infants in the multisensory and the unisensory exploration conditions. The results of the ANCOVA replicated those of the ANOVA: The main effects of exploration type, $F(1, 23) = 9.71$, $p < .01$, $\eta_p^2 = .30$, and screen, $F(1, 23) = 4.56$, $p < .05$, $\eta_p^2 = .17$, were significant. In addition, the Exploration Type × Test Event interaction, $F(1, 23) = 5.32$, $p < .05$, $\eta_p^2 = .19$, was also significant. Hence, even when group differences in familiarization looking times were controlled for, the test analysis yielded a significant Exploration Type × Test Event interaction.

The results of Experiment 4 suggest two conclusions. First, infants do not simply transfer information about the number of objects seen in the preexposure trials to the test trials. In both conditions, infants saw two spatiotemporally distinct objects in the preexposure trials. Yet the infants in the unisensory exploration condition did not interpret the test event as involving two objects. Second, these data provide converging evidence for the conclusion that combined visual and tactile exploration is critical to this type of color priming. Even when spatiotemporal information signals the presence of two distinct objects—a green ball and a red ball—infants do not attend to color information unless they are allowed simultaneous visual and tactile exploration of the balls.

These results may appear in conflict with other data suggesting that spatiotemporal information is fundamental to the individuation process. For example, if infants are given clear spatiotemporal information, in the apparatus and immediately prior to the test event, about the number of objects present (e.g., infants are shown two objects simultaneously), they use that information as the basis for individuating objects (Aguiar & Baillargeon, 2002; Wilcox & Schweinle, 2003; Xu & Carey, 1996). Why does spatiotemporal information presented during the preexposure trials fail to facilitate performance in the test trials? Infants' success in this task depends on being primed, through multisensory experiences, to attend to color information. If infants are not primed to attend to color, they have no way to distinguish between the ball seen to the left of the occluder and the ball seen to the right during the green ball–red ball test event (i.e., the balls are identical in appearance except for their color). Since infants do not assume that because two objects were seen in the preexposure trials that two objects are involved in the test event, the individuation process fails. We suspect, however, that if the green ball and the red ball were presented simultaneously in the apparatus directly prior to the experiment, showing infants that two distinct objects were present in the apparatus, the infants would respond as if they interpreted the test event as involving two objects. Notice, however, that in this situation, object individuation would not require the use of color information: It would be based solely on spatiotemporal information.

In the next experiment, we examined the extent to which the multisensory priming procedure facilitates younger infants' use of color information in an individuation task.

Experiment 5A

Wilcox and Chapa (2004) reported that another priming procedure, in which color predicted the function of an object, increased sensitivity to color information in 9.5-month-olds and even in 7.5-month-olds under some conditions. These findings led us to question whether the multisensory procedure would be effective with younger infants. To address this question, we tested 9.5-month-olds using the multisensory exploration procedure.

Method

Participants

Participants were 16 healthy full-term infants, 8 male and 8 female (mean age = 9 months, 14 days; range = 9 months, 1 day to 9 months, 29 days). Parents reported race/ethnicity as Caucasian ($n = 13$) or Hispanic ($n = 3$). Five additional infants were tested but eliminated because of fussiness ($n = 3$) or procedural problems ($n = 2$). Eight infants were randomly assigned to each of two conditions (narrow or wide screen).

Apparatus, Test Events, Procedure

The apparatus, test events, and procedure were identical to those of Experiment 2. Interobserver agreement during the test trials was measured for all 16 infants and averaged 93%.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model ANOVA with trial as the within-subject factor and condition (narrow or wide screen) as the between-subjects factor. The main effect of trial was significant, $F(5, 70) = 20.62$, $p < .001$, $\eta_p^2 = .60$, indicating that looking times decreased significantly across familiarization trials. The infants' looking times averaged across Trials 1 and 2 (M = 43.4 s, SD = 15.2) were greater in magnitude than those averaged across Trials 3 and 4 (M = 25.9 s, SD = 10.7), and they decreased further during Trials 5 and 6 (M =17.2 s, SD =5.3). The main effect of condition was not significant, $F(1, 14) = 3.67$, $p > .05$. The infants in the narrow-screen (M = 26.7 s, SD = 8.9) and the wide-screen (M = 32.2 s, SD = 6.3) conditions looked about equally during the familiarization trials. However, the Trial × Condition interaction was significant, $F(5, 70) = 3.43$, $p < .01$, $\eta_p^2 = .20$. Inspection of the familiarization data revealed that the mean looking times of the wide-screen infants, averaged across Trials 1 and 2 (M = 52.6 s, SD = 8.9), were greater than those of the narrow-screen infants (M = 34.2 s, SD = 15.0). In addition, the wide-screen infants demonstrated a greater decrease in looking times as the familiarization trials progressed, as is evident by the looking times averaged across Trials 3 and 4 (wide-screen condition, M = 26.9 s, SD = 11.6; narrow-screen condition, M = 24.9 s, SD = 10.3) and Trials 5 and 6 (wide-screen condition, M = 17.1 s, SD = 4.7; narrow-screen condition, M = 17.3 s, SD = 6.3). Note that the mean looking times of the narrow- and wide-screen infants were similar by Trials 3 and 4 and almost identical by Trials 5 and 6. Hence, we were not concerned about group differences in visual attention during the test trials.

Test Trials

The infants' looking times during the two test trials (see Figure 3) were analyzed in the same manner as the familiarization trials. The main effect of trial, the main effect of condition, and the Trial × Condition interaction were not significant, $Fs(1, 14) < 2$. The infants in the narrow-screen (M = 19.5 s, SD = 9.3) and the wide-screen (M = 22.0 s, SD = 16.8) conditions looked about equally during the test trials.

The test data were also analyzed together with those obtained in Experiment 2 with the 10.5-month-olds by means of a one-way ANOVA with age (9.5 or 10.5 months) and event (narrow or wide screen) as between-subjects factors. There were no significant main effects or interactions involving trial in Experiments 2 and 5A; hence test data were collapsed across this factor. The analysis revealed a significant interaction between age and event, $F(1, 28) = 5.97$, $p < .025$, $\eta_p^2 = .18$, indicating that the 9.5- and 10.5-month-olds responded differently to the test events.

Exploring Age-Related Differences in the Effectiveness of Multisensory Priming

Why does visual and tactile exploration facilitate the use of color information in 10.5-month-olds but not in 9.5-month-olds? There are at least two possible explanations. One is that 9.5- and 10.5-month-olds engage in different behaviors during the preexposure trials, some of which are more likely to support multisensory priming than others. For example, perhaps 10.5-month-olds are more active in their exploration of the objects or spend more time in combined visual and tactile exploration. Different exploratory behaviors could give infants access to different types of

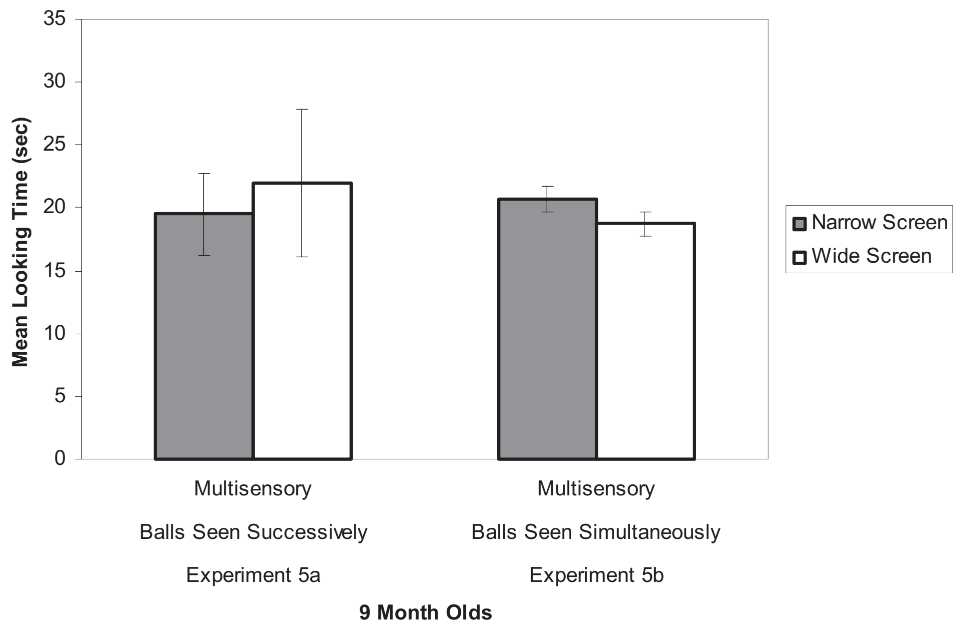

Figure 3. Mean looking times (in seconds) of the 9.5-month-old infants in Experiments 5A and 5B to the test events. Vertical lines depict standard errors of the means.

object information. Alternatively, the exploration behaviors of 9.5- and 10.5-month-olds during the preexposure trials may not differ reliably but 9.5-month-olds may not be as skilled at coding or using that information.

One way to address this issue is to examine infants' exploratory behaviors during the preexposure trials. We had videotaped preexposure trials for 10 of the 10.5-month-olds tested in Experiment 2 and 12 of the 9.5-month-olds tested in Experiment 5A. The visual and tactile exploration behaviors of both groups of infants were coded using Observer Video-Pro software (Noldus Information Technology, Wageningen, the Netherlands). Although the small sample size limits the conclusions that can be drawn from analyses of the exploratory behaviors, inspection of the data that are available may shed light on the extent to which 9.5- and 10.5-month-olds interact differently with the balls during the preexposure trials.

The following variables were coded during each 60-s preexposure trial: the amount of time infants spent looking at the object (e.g., looking at the ball without touching it), acting on the object (e.g., tapping, scratching, rubbing, grasping, mouthing, banging, rolling the ball, while either looking at or not looking at the ball), and in combined visual and tactile exploration of the object (i.e., were simultaneously touching and looking at the ball). The 10.5- and 9.5-month-olds did not differ reliably in the total time, summed across the two preexposure trials, that they spent looking at the balls (9.5 months, $M = 19.0$ s, $SD = 9.7$; 10.5 months, $M = 25.8$ s, $SD = 24.8$), acting on the balls (9.5 months, $M = 85.4$ s, $SD = 20.6$; 10.5 months, $M = 82.4$ s, $SD = 39.0$), or in combined visual and tactile exploration of the balls (9.5 months, $M = 35.3$ s, $SD = 17.0$; 10.5 months, $M = 26.9$ s, $SD = 16.0$). Together, these preliminary results suggest that the two age groups did not vary reliably in their exploratory behaviors during the preexposure trials.

At the same time, these preliminary results need to be interpreted with caution. First, it is possible that there are differences between the two age groups that were not captured in this pilot work. For example, perhaps analysis of specific exploratory behaviors (e.g., rolling or tapping) with a larger sample size would reveal subtle age differences. Second, it is possible that even though the 9.5- and 10.5-month-olds engaged in the same exploratory behaviors during the preexposure trials, they did not acquire the same information from that interaction. Third, to fully understand the relation between multisensory exploration and object individuation, we would need to assess the extent to which infants' preexposure behaviors predict performance on the individuation task. It is possible that the type of behaviors in which infants engage is a better predictor of performance on the individuation task than age. For example, subsequent research may reveal that although the two age groups do not differ significantly in the type of behaviors in which they engage, there is a significant correlation between behavior type and performance on the individuation task.

Experiment 5B

Given the effectiveness of color-function priming with 9.5- and 7.5-month-olds (Wilcox & Chapa, 2004), we found the outcome of Experiment 5A unexpected. To assess whether 9.5-month-olds would benefit from multisensory priming under more supportive conditions, we tested an additional group of infants using the simultaneous presentation procedure of Experiment 4.

Method

Participants

Participants were 14 healthy full-term infants, 8 male and 6 female (mean age = 9 months, 14 days; range = 9 months, 3 days to 9 months, 27 days). Parents reported race/ethnicity as Caucasian (n = 11), Hispanic (n = 1), Black (n = 1), or mixed race of Hispanic and Black (n = 1). One additional infant was tested but eliminated because the parent labeled the ball during the test trials. Seven infants were randomly assigned to each of two conditions (narrow or wide screen).

Apparatus, Test Events, Procedure

The apparatus, test events, and procedure were identical to those of the multisensory condition of Experiment 4. Interobserver agreement during the test trials averaged 92% per test trial per infant.

Results and Discussion

Familiarization Trials

The infants' looking times during the six familiarization trials were analyzed by means of a mixed-model ANOVA with trial as the within-subject factor and condition (narrow or wide screen) as the between-subjects factor. The main effect of trial was significant, $F(5, 60) = 7.38$, $p < .001$, $\eta_p^2 = .38$, indicating that looking times decreased significantly across familiarization trials. The infants' looking times averaged across Trials 1 and 2 (M = 40.0 s, SD =12.4) were greater in magnitude than those averaged across Trials 3 and 4 (M = 25.2 s, SD = 9.9) and Trials 5 and 6 (M =23.8 s, SD =12.1). The main effect of condition was not significant, $F(1, 12) < 1$, nor was the Trial × Condition interaction, $F(5, 60) < 1$. The infants in the narrow-screen (M = 26.7 s, SD = 8.9) and the wide-screen (M = 32.2 s, SD = 6.3) conditions looked about equally during the familiarization trials.

Test Trials

The infants' looking times during the two test trials (see Figure 3) were analyzed in the same manner as the familiarization trials. The main effect of trial was significant, $F(1, 12) = 5.48$, $p < .05$, $\eta_p^2 = .31$, indicating that the infants' mean looking times decreased across trial (Trial 1, M = 25.5 s, SD = 19.2; Trial 2, M = 14.0 s, SD = 8.6). The main effect of condition and the Trial × Condition interaction were not significant, $Fs(1, 12) < 1$. The infants in the narrow-screen (M = 20.7 s, SD = 13.6) and the wide-screen (M = 18.7 s, SD = 11.1) conditions looked about equally during the test trials. Even when the objects were presented simultaneously during the preexposure trials so that infants could easily establish two distinct object representations, the 9.5-month-olds failed to use the color difference to individuate the objects.

General Discussion

Five experiments were conducted to investigate the extent to which multisensory (visual and tactile) and unisensory (visual only) exploration of objects prior to an individuation task can facilitate 10.5- and 9.5-month-old infants' use of color information as the basis for individuating those objects. The results revealed that combined visual and tactile exploration of the objects, but not visual exploration alone, increased 10.5-month-olds' sensitivity to color differences in the individuation task. This outcome was obtained regardless of whether the objects were presented successively or simultaneously in the preexposure trials (Experiments 2 to 4). In contrast, 9.5-month-olds failed to benefit from the multisensory experience (Experiments 5A and 5B). The positive results obtained in the multisensory exploration conditions add to a growing body of research that suggests that infants' object and event representations are relatively fluid and can be altered by select experiences. They also provide converging evidence for the conclusion that infants younger than 11.5 months can be primed to attend to color information in an individuation task, even though they do not typically attend to color differences as the basis for individuating objects.

At the same time, these results raise new questions about the nature and development of infants' object representations. For example, why does combined visual and tactile exploration lead 10.5-month-olds to attend to color information? Why do younger 9.5-month-olds fail to benefit from multisensory exploration? What does this reveal about infants' changing capacity to attend to and use color information when tracking objects through occlusion? In order to address these and related questions, we have organized the remainder of the General Discussion into three sections. The first section focuses on the cognitive mechanisms that support multisensory priming in infants. The second section focuses on the underlying basis for age-related changes in infants' capacity to benefit from the multisensory experience. The third, and final, section focuses on the nature of the representations that support color priming.

Cognitive Mechanisms That Support Multisensory Priming

Why does visual and tactile exploration of the objects prior to an individuation task, but not visual exploration alone, increase infants' sensitivity to color information? One explanation, and the one we offered earlier, is that combined visual and tactile exploration of objects recruits attention and facilitates the formation of more detailed and robust representations than visual exploration alone. More specifically, simultaneously looking at and physically manipulating an object provides infants with the opportunity to encode amodal object properties (e.g., shape) in two different modalities. The redundancy in information that this experience affords facilitates the formation of a multimodal object representation. Once multimodal representations are formed, infants' attention is then directed toward unimodal features. This experience highlights color features as an integral part of the objects, leading infants to attend to color differences in the individuation task. The explanation just offered is supported by a body of research that has revealed that infants are more likely to attend to modality-specific information, such as color, during object processing tasks when they are allowed multimodal experiences with the objects (Bahrick & Lickliter, 2000, 2002; Hernandez-Reif & Bahrick, 2001; Slater et al., 1999).

There is an alternative interpretation of these results, however, that should be considered. This alternative interpretation focuses on a more simplistic attentional mechanism and does not involve sensory integration. According to this interpretation, manual exploration of an object directs infants' attention to information that lies on the surface of the object. Once infants are focused on the object's surface they are led to attend to surface properties, such as color. Without this directed attention, infants focus instead on object properties they view as more relevant to understanding objects and interpreting physical events. This explanation predicts that although touching the ball is beneficial, it is not required in order for color priming to occur. Any experience that draws infants' attention to surface properties should produce the same result. For example, if infants' attention could be drawn to the surface of the ball by having the experimenter point to the surface of the ball, or by having the experimenter manually explore the ball while the infant observed, infants should demonstrate increased sensitivity to color information. To contrast alternative interpretations, the multisensory integration hypothesis predicts that simply directing infants' attention to the surface of the ball, or any manipulation that does not allow for multimodal coding of objects, will not lead to increased sensitivity to color information. Directed attention is necessary but not sufficient for color priming to occur: Multisensory experiences are also required. Although we suspect that drawing infants' attention to the surface properties in the absence of visual and tactile exploration will not support color priming, future research will be needed to test these two hypotheses.

The Underlying Basis for Age-Related Changes in Multisensory Priming

In light of recent evidence that infants 9.5 months of age and younger can be primed to attend to color differences using the color-function procedure (Wilcox, 2004; Wilcox & Chapa, 2004), we were surprised to find that the 9.5-month-olds did not benefit from the multisensory procedure. Even when the objects were presented simultaneously in the preexposure trials, easing processing demands, 9.5-month-olds failed to integrate color information into their object representations. In order to gain insight into this developmental progression, we coded and analyzed visual and tactile behaviors of 9.5- and 10.5-month-olds during multisensory exploration of objects. The results suggested that the 9.5- and 10.5-month-olds did not differ reliably in the type of behaviors they engaged in during multisensory exploration. These results, although preliminary, suggest that although 9.5- and 10.5-month-olds have access to the same information (i.e., their exploratory behaviors give them access to the same information), the older infants are more skilled at encoding and/or using that information. Future research that examines the extent to which visual and tactile exploration during the preexposure trials predicts performance during the test trials will be needed to fully understand the relation between multisensory exploration and object individuation.

One additional question that is raised by the results obtained with the 9.5-month-olds is whether infants' capacity to benefit from multisensory priming is limited by the age at which infants first demonstrate sensitivity to the surface feature under study, or by age more generally. For example, when the multisensory priming procedure was used, infants demonstrated sensitivity to color information at 10.5 months but not 9.5 months. That is, infants benefited from the multisensory exploration procedure in the month prior to when they use color spontaneously, but not before. One possible explanation for this pattern of results is that regardless of the surface feature under study, multisensory priming is effective only in the month prior to when infants use that feature spontaneously. So, for example, if infants first use pattern differences to individuate objects at 7.5 months, the multisensory procedure would prime 6.5-month-olds but not 5.5-month-olds to attend to pattern differences in an individuation task. According to this hypothesis, there is a window of opportunity, immediately prior to when infants spontaneously use a surface feature, in which multisensory experiences can facilitate infants' use of that surface feature. In other words, multisensory exploration is a relatively general priming mechanism that can be applied at many different ages to enhance sensitivity to a wide range of surface features, as long as it is applied during the "window of opportunity" for the feature under study. Such a mechanism would be quite useful for learning about objects, because infants of almost all ages engage in manual exploration behaviors on a daily basis. An alternative explanation is that multisensory priming is only effective in infants 10.5 months and older regardless of the surface feature to be primed. If this were the case, the multisensory priming procedure could not be used to prime 6.5-month-olds to attend to pattern information, but it could be used to prime 10.5-month-olds to attend to luminance information (infants first use luminance differences to individuate objects at 11.5 months, Woods & Wilcox, 2006a). According to this hypothesis, there is something unique about the way that infants 10.5 months of age and older process multisensory information that allows them to benefit from the multisensory procedure. We are currently testing these two hypotheses, and preliminary data (Woods & Wilcox, 2006b) lead us to favor the first hypothesis: that multisensory priming is a more general mechanism that is effective at a wide range of ages given the appropriate feature.

The Nature of the Representations That Support Color Priming

To fully specify a priming mechanism, whether it be feature-function priming or multisensory priming, we must understand the nature of the representations that are laid down during the priming experience. Recently, Wilcox and her colleagues have focused on the level of specificity (or abstraction) at which infants represent color-function events. For example, recall the pound–pour experiments. The infants could have represented the pound–pour pretest events as (a) green objects and red objects perform different functions or (b) different-colored objects perform different functions. These make different predictions about the kind of information to which infants will be primed. The first predicts that infants will be primed to attend to the difference between green and red, whereas the second predicts that infants will be primed to attend to color differences more generally. To test these predictions, Wilcox, Woods, and Chapa (2006) tested 9.5-month-olds using a procedure that differed from the pound–pour procedure in two ways. First, the pound–pour events were replaced with stir–lift events: Green spoons stirred salt in a bowl, and red spoons lifted a bowl by a hook. Second, the colors of the spoons seen in the stir–lift events were the same as (i.e., green and red) or different from (i.e., yellow and blue) the colors of the balls. If infants are primed to attend only to the color difference seen in the stir–lift event, then the infants in the same-colors condition but not the different-colors condition should successfully individuate the green and the red balls. In contrast, if infants are primed to attend to color differences more generally, then the infants in both conditions should individuate the green and the red balls. The results indicated that the infants in the same-colors condition looked reliably longer at the narrow-screen than at the wide-screen test event. In contrast, the infants in the different-colors condition looked about equally at the two test events. The infants were primed to attend only to the color difference seen in the stir–lift events, suggesting that their representation of the events was quite specific. Additional results have revealed, however, that if each color–function pair is seen with a different pair of colors (i.e., yellow–blue and purple–orange), so that the category exemplars are more variable, or if the stir–lift spoons are presented together during the test events, so that the exemplars in each pair can be directly compared, 9.5-month-olds form more inclusive event categories and will generalize across color in the test events (Wilcox et al., 2006). Hence, the nature of the exemplars infants see in the pretest events determines the type of information infants include in their event representations and, in turn, the type of information to which infants attend in a subsequent individuation task.

In contrast, we know very little about the nature of the representations that are laid down during the multisensory experience. Are the representations that support multisensory priming specific or abstract? For example, if infants were shown objects in the preexposure trials that differed in kind from those seen in the test trials but were of the same color (e.g., a green truck and a red truck), would infants show sensitivity to the difference between green and red in the test event? What if infants were shown objects in the preexposure trials that were of the same kind but differed in color (e.g., yellow and blue balls and/or purple and orange balls) from those of the test event? The conditions under which infants generalize to the test event (i.e., show sensitivity to color differences) would reveal the specificity with which infants represent the preexposure trials. The outcome of studies like these would allow us to determine the nature of the representations that support multisensory priming and to identify the extent to which the feature-function and the multisensory procedures produce representations that have similar levels of specificity. Generally speaking, the more we know about the conditions under which feature-function and multisensory priming are supported, the better understanding we will have about the extent to which these two priming mechanism differ (or are similar).

Final Comments

The results obtained in the series of experiments presented here shed light on how an everyday experience—combined visual and tactile exploration of objects—can promote learning about objects as individual entities. This experience, in which infants routinely engage, can have profound effects on the type of information to which infants attend when individuating objects. The present results also demonstrate just how flexible infants' object representations can be. Sensitivities are dependent, at least to some extent, on infants' recent experiences. We are confident that further investigation using the multisensory procedure and its variants will reveal important information about the structure of early object knowledge, the types of experience that can alter this knowledge, and the mechanisms by which this occurs.

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