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# The emergence of object-based visual attention in infancy: A role for family socioeconomic status and competing visual features

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**Abstract**

The development of spatial visual attention has been extensively studied in infants, but far less is known about the emergence of object-based visual attention. We tested 3–5- and 9–12-month-old infants on a task that allowed us to measure infants' attention orienting bias toward whole objects when they competed with color, motion, and orientation feature information. Infants' attention orienting to whole objects was affected by the dimension of the competing visual feature. Whether attention was biased toward the whole object or its salient competing feature (e.g., "ball" or "red") changed with age for the color feature, with infants biased toward whole objects with age. Moreover, family socioeconomic status predicted feature-based attention in the youngest infants and object-based attention in the older infants when color feature information competed with whole-object information.

## 1 | INTRODUCTION

Attention improves the quality of early visual processing by enhancing contrast sensitivity, acuity, and perceptual processing in the service of learning and memory (Carrasco, 2011; Carrasco, Ling, & Read, 2004; Neisser & Becklen, 1975). Visual attention is often considered in spatial terms, whereby a "spotlight" highlights relevant information in the visual environment (Carrasco, 2011). However,

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*what* attention is allocated to is as important as *where* it is deployed. Although the development of spatial visual attention over the first year of life has been extensively studied (Amso & Johnson, 2006, 2008; Clohessy, Posner, Rothbart, & Vecera, 1991; Hood, 1993; Johnson, Posner, & Rothbart, 1991; Johnson & Tucker, 1996; Markant & Amso, 2013, 2016), much less is known about the development of object-based attention (OBA).

An "object" is defined as a set of perceptually grouped visual features that adhere to Gestalt principles such as proximity, good continuation, and closure (Feldman, 2003; Scholl, 2001; Watson & Kramer, 1999). When attention selects a whole object, its constituent parts benefit from further processing (e.g., Schoenfeld, Hopf, Merkel, Heinze, & Hillyard, 2014; for reviews, see Chen, 2012; Scholl, 2001). Historically, OBA has been studied by using spatial cues to guide attention orienting. For instance, Egly, Driver, & Rafal (1994) used a cue to prime the presence of a target either *within* an object, or equidistant but appearing as part of *different* objects. With OBA, subsequent processing is enhanced for a target appearing anywhere *within* the same object, relative to an equidistant target that is part of a *different* object. This paradigm has been adapted to show that 8-month-old infants show a similar OBA benefit for shapes (Bulf & Valenza, 2013; Johnson & Gilmore, 1998) and for inverted faces, but not upright faces (Valenza, Franchin, & Bulf, 2014), suggesting OBA interacts with social and nonsocial stimuli differently. More recent adult work has used a variety of spatial and nonspatial paradigms to examine the mechanisms underlying OBA (Avrahami, 1999; Cepeda & Kramer, 1999; Chen & Cave, 2006; Chen & Cave, 2008; Lamy & Egeth, 2002; Shomstein & Behrmann, 2006, 2008; Shomstein & Yantis, 2002, 2004). As noted by Baldauf and Desimone (2014), "how we attend to objects and their features that cannot be separated by location is not understood."

One OBA mechanism identified by Shomstein and Yantis (2002; see also Drummond & Shomstein, 2010) is called the *attentional prioritization* hypothesis. Naturalistic visual scenes contain information from multiple feature channels (e.g., color, motion, form, and orientation) that compete for attentional allocation in parallel. OBA is the product of the visual system assigning higher attentional priority to the elements *within* an attended object. By this view, attention must select the whole object for its constituent parts to receive the subsequent processing benefit (e.g., Schoenfeld et al., 2014; for reviews, see Chen, 2012; Scholl, 2001). Moreover, it follows that this attentional priority allocation is also influenced by the similarity of the enhanced object relative to the target object template (Cave & Wolfe, 1990; Shomstein & Behrmann, 2008; Wolfe, 1994).

Developmentally, OBA is intimately bound to object perception, which shows a great deal of change until about 4 months of age (e.g., Johnson, Amso & Slemmer, 2003, 2004; Kellman & Arterberry, 2006). As such, the benefits of OBA may be dependent also on whether infants are *able* to select the whole object and/or its form when that information competes with simultaneously occurring salient features such as color, orientation, and motion information. In contrast to OBA, feature-based attention would benefit processing of the otherwise defining object feature regardless of infants' ability to select the whole object. Here, we examine this issue regarding how whole object/form information interacts with competing visual features for attentional priority, which is paramount to understanding the visual mechanisms underlying OBA development in infancy.

A recent organizing framework for visual attention development, the visual cascade model (Amso & Scerif, 2015), offers an opportunity to make biologically plausible predictions relevant to the mechanisms supporting OBA development. In brief, this model posits that visual development may be a necessary ontogenetic beginning of visual attention development. As visual processing in multiple feature channels develops, so does competition among those features for attentional selection. The human visual cortex is organized hierarchically, with relatively distinct anatomical pathways for processing of motion information (dorsal visual pathway) and color information (ventral visual pathway) (Ungerleider & Haxby, 1994; Van Essen & Maunsell, 1983). Object processing and recognition

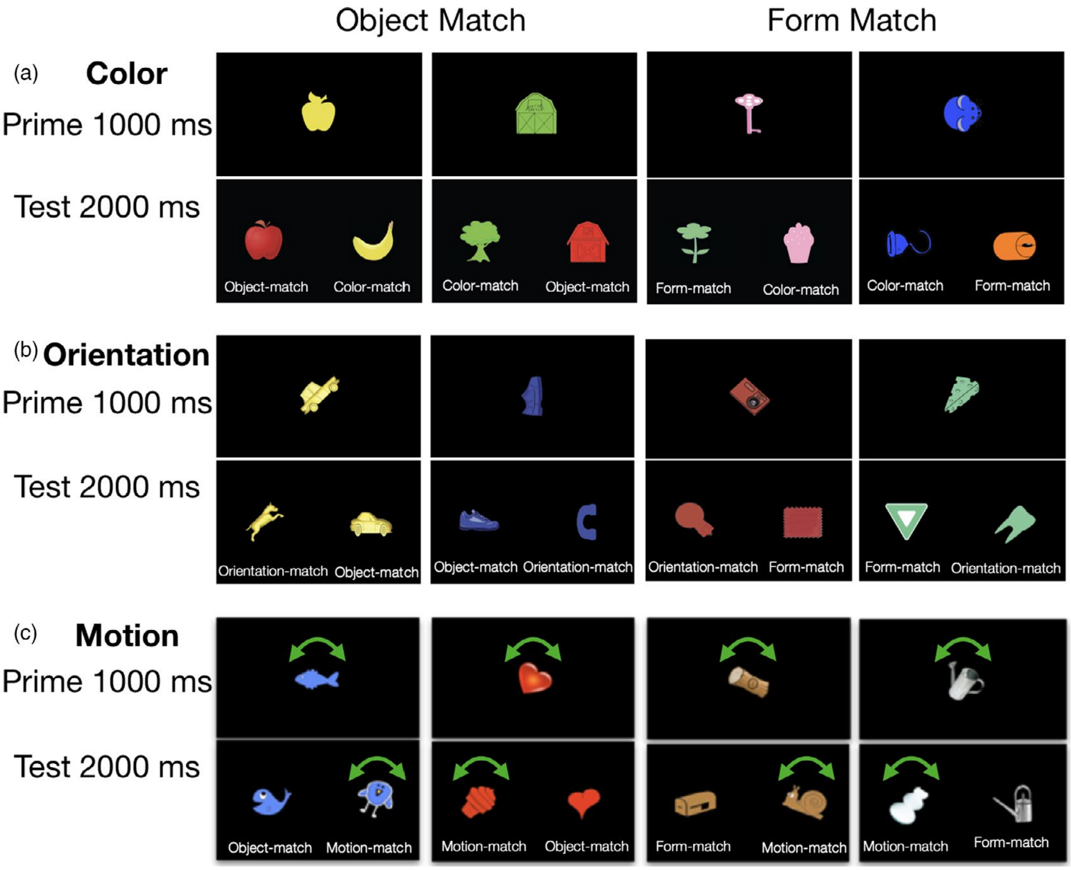

**FIGURE 1** Schematic of all 12 trials in the task. In each trial, infants were primed with a centrally presented item for 1,000 ms, after which they immediately saw two test items. One test item matched the color, orientation, or motion of the prime but was paired with a different object form. The other item matched the object/form of the prime (object-match, form-match), but not the previously presented color, motion, or orientation feature. Green double-headed arrows (not displayed to infants) represent rotational object motion. Stimulus locations were counterbalanced

involve the ventral visual pathway as early as 6 months (Emberson, Crosswhite, Richards, & Aslin, 2017). Visual features including orientation and color are processed earlier in the hierarchy (areas V1-V4), while relatively complex object representations are processed later in the hierarchy (inferotemporal cortex). In contrast, motion information, processed in the dorsal visual pathway, would not feed directly into cortical regions involved in object processing. Thus, our first prediction is that in infancy, when cortical connectivity is dominated by short-range relative to long-range connections (Gao et al., 2011), selection of the object in the presence of competing visual features (OBA) will be evident when orientation and color compete with object information, but not when motion competes with object information.

Our second prediction is that the emergence of OBA should vary by individual differences in the developmental processing of the visual feature in question. Visual development undeniably depends on visual experience (Hubel & Wiesel, 1970; Shatz & Strykert, 1978). It follows that individual differences in visual experience may drive individual differences in visual processing, and ultimately in OBA development. Broadly, the developmental literature has used home socioeconomic status (SES) as an index of environmental enrichment (Amso, Salhi, & Badre, 2019; McLoyd, 1998). Higher SES homes are characterized by access to a greater variety of objects, toys, books, and other complex visual stimuli (Bradley, Corwyn, Mcadoo, & Coll, 2001). Accumulating evidence indicates a relation between SES and infant visual development. For instance, one study showed that family income predicted attention to faces, a class of objects, in infants (Amso, Haas, & Markant, 2014). Another longitudinal study in 6–12-month-olds found that high-SES infants outperformed low-SES infants on measures of focused attention, particularly as the number and complexity of presented objects increased (Clearfield & Jedd, 2012). In yet another study, Tacke, Bailey, and Clearfield (2015) showed that high-SES but not low-SES infants used information learned from object or surface exploration to recognize new opportunities for object exploration. Taken together, these studies suggest that SES may have some explanatory power with respect to normative variability in infant visual experience.

To test these predictions, we presented 3–5- and 9–12-month-olds with a series of displays intended to understand how OBA interacts with developing competing visual features. Infants were first primed with an object image (prime item), after which they immediately saw two test items presented side-by-side (see Figure 1 for depiction of all test stimuli). One test item (object/form-match) matched the prime in object form but differed from the prime along a salient feature dimension—color, orientation, or motion. The other competing test item (feature-match) differed in object form but matched the prime along the feature dimension. Within the object/form-match test items, we included items that matched the prime only on basic form or shape (form-match) as well as on form + identifying object characteristics (object-match). This manipulation was designed to ensure that infants were not matching simply based on the form of the item (featural information), but were also encoding identifying object characteristics.

We measured the distribution of infants' visual attention orienting to object/form-match and feature-match items at test, interpreting orienting to indicate that that item had been selected for attentional priority during the brief prime, and that this selection resulted in continued attentional priority during the test display presentation. We designed the task timing parameters to adhere to similar tasks in the visual attention literature, as relevant to infants 12 months and under (e.g., Amso & Johnson, 2005, 2008; Markant & Amso, 2013). Spatial cueing paradigms, where a cue elicits an enhancement toward a stimulus with short delays and suppression with long delays, would suggest that a cue (here a prime), followed immediately by a probe stimulus, should benefit or facilitate the stimulus feature that is currently enhanced (e.g., Markant & Amso, 2013). The same results are true for negative priming studies, where there is an enhancement of attended information with short delays between prime and probe-target displays (Amso & Johnson, 2005, 2008).

# 2 | METHOD

## 2.1 | Participants

The final sample consisted of 22 3- to 5-month-old infants ($M = 133.3$ days, $SD = 14.6$ days; 12 girls) and 26 9- to 12-month-old infants ($M = 305.7$ days, $SD = 35.0$ days; 17 girls). Infants were recruited via community advertisements and birth records obtained from the state Department of Health. The study was conducted according to guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each infant before any assessment or data collection. All procedures involving human subjects in this study were approved by the Institutional Review Board at Brown University. All infants were born full-term (within 4 weeks of due date) and had no history of serious health problems. An additional nine infants were tested but excluded from the final sample due to an inability to obtain an eye-tracking calibration ($n = 4$, 3–5 months, $n = 4$, 9–12 months) or due to only contributing one trial of data in total ($n = 1$, 3- to 5-month-olds).

## 2.2 | Materials

### 2.2.1 | Apparatus

Infants sat on a parent's lap approximately 60 cm away from a 22” monitor in a dimly lit experimental room. Looking data were collected at a rate of 60 Hz using a SensoMotoric Instruments (SMI) RED eye tracker attached to the bottom of the monitor. A digital video camera provided the experimenter with a live view of the infant and recorded the infant's general looking behavior. Prior to the task, each infant's point of gaze (POG) was calibrated by presenting a looming stimulus in the upper left and lower right corners of the screen until it was fixated by the infant. To validate this calibration, the same stimulus was presented in four locations on the screen and the infant's estimated POG was compared with the stimulus location.

### 2.2.2 | Stimuli

Stimuli (all displays shown to infants are presented in Figure 1) were presented using SMI Experiment Center software. Stimuli were drawings of objects presented on a black background. Each item was approximately 8.5 cm by 8.5 cm (8° visual angle) when presented on the screen. The task consisted of a series of trials with a *prime* display followed by a *test* display (Figure 1). Prime displays consisted of a single item presented in the center of the display. Test displays consisted of two items presented side-by-side, with a center-to-center distance between items of approximately 25.2 cm (23.7° visual angle).

## 2.3 | Procedure

Before each trial, an attention-getting stimulus was presented in the middle of the screen to center infants’ orienting. When the experimenter judged that the infant was looking at the attention-getter, she pressed a key to initiate the trial. The prime stimulus was presented in the center of the screen and remained visible for 1,000 ms. The prime stimulus then disappeared, and the test display appeared immediately and remained visible for 2,000 ms.

Infants saw displays from three feature conditions (color, orientation, motion). For the color condition, infants saw a prime item (e.g., yellow apple) that was followed by a display containing both an object/form-match item and a feature-match item (Figure 1). The feature-match item matched the prime on color but not object/form. The object/form-match item matched on object/form but not color. For the orientation condition, infants saw a prime item that was rotated at 45° or 90° angles from clockwise. This was followed by the test display containing both an object/form-match item and also a feature-match item that was defined by a different form but was oriented at the same angle as the prime item. For the motion condition, the prime item rotated back and forth at 3 Hz subtending approximately 45 degrees from center on screen. At test, the object/form-match item was static, while the feature-match item moved akin to the prime.

Infants saw 12 trials (all stimuli are shown in Figure 1), with an equal number of trials (4) from each feature type (color, orientation, motion). Within each feature type, infants saw two object-match and two form-match trials. This manipulation was designed to ensure that infants were not simply matching on the basic form or shape of the item, but were also encoding identifying object characteristics. We expect object and form matches to have highly similar 2D Fourier (spatial frequency) spectra, meaning that the size and shape dimensions required to transform the images into 2D object

**TABLE 1** Summary statistics for eye-tracking metrics

| | **3–5-month-olds (*n* = 22)** | **9–12-month-old (*n* = 26)** | **All (*N* = 48)** |
|---|---|---|---|
| | ***M* (*SD*)** | ***M* (*SD*)** | **Mean** |
| Tracking ratio | 87.27 (11.34) | 90.59 (9.32) | 89.07 (10.32) |
| Fixation count | 3.76 (0.61) | 3.39 (0.63) | 3.56 (0.64) |
| Mean fixation dispersion (px) | 74.79 (5.59) | 72.61 (7.03) | 73.61 (6.44) |
| Mean saccade duration (ms) | 86.58 (45.80) | 73.68 (34.40) | 79.59 (40.11) |
| Mean saccade latency (ms) | 280.16 (103.99) | 304.60 (98.48) | 293.40 (100.70) |

representations are very similar. The right/left of center of the test items was counterbalanced within each subgroup of trials (e.g., on color trials, the feature-match appeared on the left once and on the right once), and across infants for each specific stimulus set (e.g., the red apple appeared on the left for half of the infants and on the right for the other half). Trial order was randomized for each infant.

## 2.4 | Data processing

The dependent variables were: (a) proportion of trials where first looks were directed at object/form-match relative to feature-match locations, and (b) proportion of total duration of looking (out of 2,000 ms) at object/form-match relative to feature-match locations at test. Although it is possible to code right/left eye movements from video feed, we chose to use point-of-gaze data from the SMI eye tracker to measure our dependent variables to circumvent human error in coding young infant eye movements from video. Infants who did not provide >100 ms for at least one trial per condition were excluded (nine infants total). On average, infants contributed data for 3.86, 3.84, and 3.68 trials (of four possible) for color, orientation, and motion conditions, respectively. Using nonparametric tests, we compared the number of trials included for each feature condition between age group (3–5 months, 9–12 months). We found that the number of trials included did not differ by age group (all $p$'s $> .10$).

Test displays were divided in half, defined as two rectangular (23.5 cm w × 30 cm h, 21.4° × 28.1°) areas of interest (AOIs) that bisected the display area into right and left of center halves. SMI BeGaze software was used to determine the right/left location of the attention shift from center, as well as the duration of looking during each test display. Since there was no time interval between the prime and test displays, the first 250 ms of the test displays was excluded from the analyses to ensure that looking time to the center of the screen (where the prime stimulus had just been presented) was not factored into the dependent measures.

We defined an attentional right/left shift as the location of the first fixation after test display appearance. A fixation is defined here as 80 ms of continuous looking within a 100 pixel (2.7°) dispersion radius. We note that fixations are more traditionally defined as 100 ms of continuous looking, but non-smooth tracks in the youngest infants would have resulted in fewer data points for inclusion if the traditional 100 ms/100 pixel were used. Further, temporal smoothing over the data to eliminate non-smooth tracks may have confounded our attentional priority or first look detection in an age-relevant manner. That is, younger infants would have contributed differentially less data than older infants (see preliminary results on similar eye-tracking metrics by age group). Thus, since our measure is simply a machine-based calculation of right/left looks (which in human coding would not have required measurement of any fixation duration at all), we used a less conservative 80 ms estimate to define eye tracker output. We examined any possibly confounding age-linked differences in eye metrics in preliminary analyses (see Table 1). Specifically, we examined differences in tracking ratio, which is the combined percent eye-tracking data recorded during the test phase of all trials, fixation frequency, fixation dispersion, saccade duration, and saccade latency. None of these variables were significantly different by age group, all *ps* > .160.

### 2.4.1 | Attentional priority score calculations

Test display trials were coded as 0 if the infant prioritized visual attention orienting to the side of the screen where the feature-match was located first and 1 if the infant first oriented to the side of the screen where the object/form-match was located. An attentional priority score for each feature type was calculated by averaging across trials. A score >.5 indicates that infants first oriented to the object/form-match on most trials, a score <.5 indicates that infants first oriented to the feature-match on most trials, and values close to .5 indicate no preference.

### 2.4.2 | Looking time difference score calculations

Look durations were calculated for each test display by summing across all observed samples in which an infant's POG fell to the right or left of screen center at test. Difference scores were calculated for each trial by subtracting the duration of time spent looking at the feature-match from the duration of time spent looking at the object/form-match. Positive difference scores indicate longer looking to the object/form-match, negative difference scores indicate longer looking to the feature-match, and values close to zero indicate no preference.

### 2.4.3 | SES demographic questionnaire

See Table 2. Parents reported the number of years of education they completed. Occupation was assessed on a scale of 1–5 using the O*Net rankings. O*Net was developed by the US Department of Labor/Employment and Training Administration as part of a nationally recognized database on occupational information. Annual household income was reported in dollars. Household income-to-needs ratio was calculated as income divided by the poverty threshold for an analogous family size (see Figure 2 for a frequency histogram of our sample). An income-to-needs ratio of 1 indicates that a family is living at the national poverty line. Of the $N = 48$ participants, $N = 37$ provided SES data. As such, we processed SES effects separate from the main analyses in order to not constrain the sample size in our primary analyses.

**TABLE 2** Descriptive demographic statistics of sample

| | Mean | *SD* | Range (min, max) | Skewness |
|---|---|---|---|---|
| Age in months | 6.8 | 2.7 | (3.8, 12.6) | 0.29 |
| Parent education average[b] | 15.0 | 2.9 | (6.0, 19.5) | −0.94 |
| Parent occupation level average[a,b] | 3.4 | 1.1 | (1, 5) | −0.48 |
| Income (in $1,000) | 82.0 | 43.0 | (10, 190) | 0.33 |
| Income-to-needs ratio | 3.8 | 2.2 | (0.5, 9.73) | 0.64 |

[a] Parent occupational level coded using O*Net ratings available through the US Department of Labor on a scale of 1–5.

[b] Data averaged across both parents.

# 3 | RESULTS

## 3.1 | Attentional priority at test

We compared attentional priority scores in an omnibus analysis with the within-subjects variables of feature type (color, orientation, motion) and object similarity (form-match, object-match), and the between-subjects variable of age group (3–5 months, 9–12 months). This analysis resulted in a main effect of object similarity, $F(1,46) = 5.202$, $p = .027$, $\eta_p^2 = .102$, which did not otherwise interact with age group or feature type (all $ps > .073$). Infants oriented to the object/form-match item more often (i.e., engaged in OBA) when object similarity was based on form + identifying object characteristics (object-match item) compared with form-match alone, $t(47) = 2.282$, $p = .027$ (Figure 3 illustrates data from all conditions). To verify these findings, two-one-sample *t* tests were conducted comparing object-match and form-match to chance looking (.5). These tests revealed that infants engaged in feature-based attention for the form-match items, $t(47) = -2.027$, $p = .048$, but not for the object-match items, $t(47) = 1.336$, $p = .188$. Together, these data indicate that infants are not matching simply based on the basic form of the objects, but are instead matching based on the form + identifying characteristics of the objects.

The omnibus also yielded a main effect of feature type, $F(2,92) = 16.474$, $p < .001$, $\eta_p^2 = .264$, and an interaction between feature type and age group, $F(2,92) = 4.334$, $p = .016$, $\eta_p^2 = .086$. This interaction indicates that infants' relative preference for the object/form-match was affected by the dimension of the competing feature-match and that this relationship between OBA and feature dimension changed with age (Figure 3). Taken together with the main effect of object similarity in the omnibus, we followed up on the age group by feature type interaction with planned comparisons against chance performance (.5) by feature type and age group for object-match trials only.

Specifically, follow-up two-tailed one-sample *t* tests indicated that performance was significantly above chance (.5) on the orientation trials for both 3–5-month-olds, $t(22) = 2.881$, $p = .009$, and 9–12-month-olds, $t(25) = 2.309$, $p = .029$. This result indicates that both groups of infants showed attentional priority to the object-match when competing with orientation information. This same OBA effect was evident at 9–12 months for color trials, $t(25) = 3.434$, $p = .002$, but there was no preference at 3–5 months, $t(21) = .271$, $p = .789$. With respect to motion trials, we saw feature-based attention effects in 9–12-month-old infants, $t(25) = -2.848$, $p = .009$, but 3–5-month-old infants showed no preference, $t(21) = -1.312$, $p = .204$.

## 3.2 | Looking time difference score analyses

To ensure that attentional priority was not driven solely by stimulus salience, which influences first fixations in bottom-up attention orienting (Itti & Koch, 2000; Parkhurst, Law, & Niebur, 2002), we verified the attentional priority findings with an analysis of looking time across the full duration of the test trials (2 s). Looking time difference scores were compared as a function of feature type (color, orientation, motion) and object similarity (object-match, form-match) by age group (3–5 months, 9–12 months) using a mixed-effects ANOVA (see Table 3 for mean looking times per condition). This analysis resulted in an interaction between feature type and age group, $F(2,92) = 6.309$, $p = .003$, $\eta_p^2 = .121$, as well as a main effect of feature type, $F(2,92) = 123.420$, $p < .001$, $\eta_p^2 = .728$, indicating that infants' relative preference for the object/form-match was affected by the dimension of the feature-match and that this relation between OBA and feature dimension changed with age.

Follow-up comparisons between age groups were conducted for each feature type to examine the source of the age group by feature type interaction. A comparison of difference scores on color trials

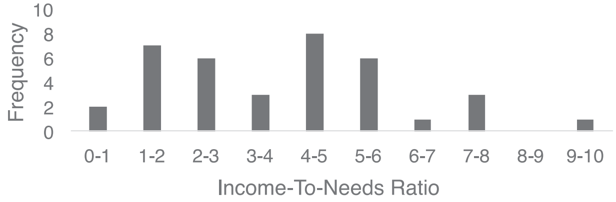

**FIGURE 2** Frequency histogram of the income-to-needs ratio measures of our sample. Nationally, an income-to-needs of 1 or less is below the poverty line and 3–4 is in the median of four-person American families (U.S. Census Bureau, 2016)

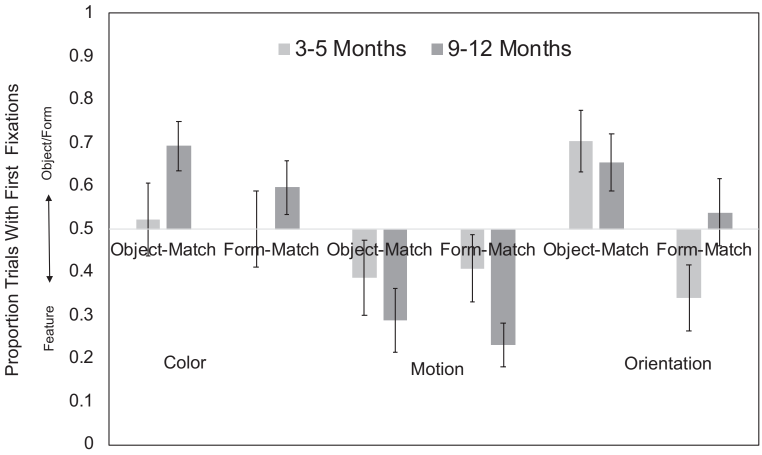

**FIGURE 3** Proportion of trials with first fixations to the object/form-match items (object-match, form-match) relative to the feature-match items, with values above chance (.5) indicating greater attentional priority to the object/form-match and below chance indicating greater attentional priority to the feature-match

**TABLE 3** Mean looking times to test displays (in ms)

| | 3–5-month-olds (*n* = 22) | 9–12-month-olds (*n* = 26) |
|---|---|---|
| | ***M*** **(*SEM*)** | ***M*** **(*SEM*)** |
| Color feature-match | 747.19 (59.54) | 692.01 (35.21) |
| Color object/form-match | 747.29 (63.72) | 941.76 (35.81) |
| Motion feature-mach | 1228.48 (73.79) | 1459.65 (45.53) |
| Motion object/form-match | 378.51 (50.98) | 247.35 (31.87) |
| Orientation feature-match | 677.78 (51.06) | 717.00 (48.22) |
| Orientation object/form-match | 881.17 (63.69) | 833.66 (36.47) |

resulted only in a main effect of age group, $F(1,46) = 4.203$, $p = .046$, $\eta_p^2 = .084$, with older infants showing a stronger preference for the object/form-match than younger infants. There was also only a main effect of age group for motion trial difference scores, $F(1,46) = 7.484$, $p = .009$, $\eta_p^2 = .140$, with older infants showing a stronger preference for the feature-match than younger infants. Orientation

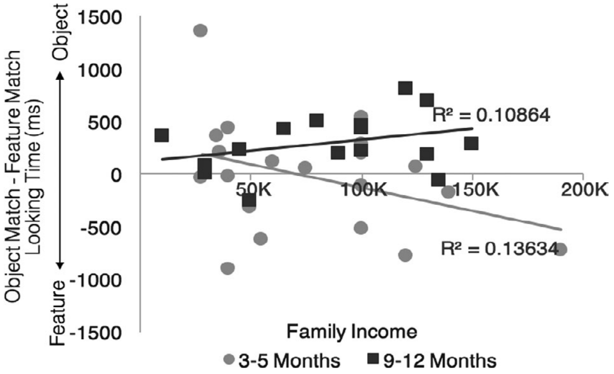

**FIGURE 4** Correlation among Income and looking time difference scores for color trials, within each Age Group. Looking time difference scores to the object-match relative to the feature-match, with positive values indicating greater looking to the object-match. Light gray represents younger infants. Dark gray represents older infants

trial difference scores did not differ by age group, $F(1,46) = .456$, $p = .503$, $\eta_p^2 = .140$. These results are overall consistent with the attentional priority scores above.

## 3.3 | SES effects on feature- and object-based attention

We next examined the relationship between SES and OBA. Our sample consisted of $N = 37$ (of the 48 total) infants who provided SES information. We reran our general attentional priority analyses and found that pattern of results held in this subsample. Occupation, education, and income were all highly correlated (all *p*s $< .005$; Table 2 reports the data from SES measures). We focus our analyses here on family income given that our predictions are about the material (e.g., toys, objects, and books) visual enrichment offered to young infants. However, we also examined parent education and saw no effects (all *ps* $> .44$).

We compared attentional priority scores across feature type (color, orientation, motion) and object similarity (object-match, form-match) by age group (3–5 months, 9–12 months), including income and the interaction of income by age group as continuous variables in an ANCOVA. This analysis revealed a significant interaction between feature type and income, $F(2,66) = 3.843$, $p = .026$, $\eta_p^2 = .104$, and a trending feature type by income by age group interaction, $F(2,66) = 3.006$, $p = .056$, $\eta_p^2 = .083$. We ran follow-up analyses comparing age group (3–5 months, 9–12 months) within each feature type, including income and the interaction of income by age group as continuous variables. We found that the main effect of income was evident in color trials, $F(1,33) = 6.255$, $p = .018$, $\eta_p^2 = .159$, but not in orientation, $F(1,33) = 0.455$, $p = .505$, $\eta_p^2 = .014$, or motion trials, $F(1,33) = 1.825$, $p = .186$, $\eta_p^2 = .052$. Likewise, the income by age group interaction was evident in color trials at a trend level, $F(1,33) = 3.910$, $p = .056$, $\eta_p^2 = .106$, but not in orientation, $F(1,33) = 0.203$, $p = .655$, $\eta_p^2 = .006$, or motion trials, $F(1,33) = 2.145$, $p = .153$, $\eta_p^2 = .061$.

We then examined looking time difference scores in an ANCOVA comparing feature type (color, orientation, motion) and object similarity (object-match, form-match) by age group (3–5 months, 9–12 months), including income and the interaction of income by age group as continuous variables. The analysis showed a feature type by income interaction, $F(2,66) = 3.269$, $p = .044$, $\eta_p^2 = .090$, and a trending feature type by income by age group interaction, $F(2,66) = 2.539$, $p = .087$, $\eta_p^2 = .071$. We next ran follow-up analyses comparing age group (3–5 months, 9–12 months) within each feature type, including income and the interaction of income by age group as continuous variables. Mirroring the attentional priority results, we found that the main effect of income was evident in color trials, $F(1,33) = 4.906$, $p = .034$, $\eta_p^2 = .129$, with higher income associated with feature matching for 3–5-month-olds and with whole-object matching for color trials in 9–12-month-olds (Figure 4). However, there was no effect of income for orientation, $F(1,33) = 0.995$, $p = .326$, $\eta_p^2 = .029$, or motion trials, $F(1,33) = 0.261$, $p = .613$, $\eta_p^2 = .008$. Likewise, the income by age group interaction was evident in color trials, $F(1,33) = 3.978$, $p = .054$, $\eta_p^2 = .108$, but not in orientation, $F(1,33) = 0.052$, $p = .821$, $\eta_p^2 = .002$, or motion trials, $F(1,33) = 0.726$, $p = .400$, $\eta_p^2 = .022$.

## 4 | DISCUSSION

Here, we examined how the emergence of OBA interacts with competing visual features. This study yielded three key findings. First, we found that OBA effects were stronger on trials where the prime item and test item matched on more than just basic form or shape information (i.e., trials where the prime and test items matched on form + identifying object characteristics). Second, and consistent with our predictions, OBA effects varied by developmental changes in the processing of the visual feature dimensions in question. Specifically, OBA was evident by 3–5 months in the orientation dimension and by 9–12 months in the color dimension. In contrast, OBA was not evident in the motion dimension in any age group and elicited feature-based attention effects in 9–12-month-olds. Finally, we found that greater family income predicted feature-based attention effects in 3–5-month-olds and OBA effects in 9–12-month-olds in the color dimension.

This approach to feature- and object-based attention supports the broad idea that visual attention is not a finite uniform process, but rather is an emergent computation from the development of the visual system (Amso & Scerif, 2015). This view is espoused best in data from saliency map studies (Itti & Koch, 2000), where orienting to a winner-take-all salient location in a visual scene is based on the linear summation of feature information across visual feature channels. Here, we make a similar argument for OBA: Whether infants select a whole object or its competing features for subsequent attentional priority will depend on the developmental strength of the competing feature. The stronger the percept of the competing feature relative to the object information, the more likely that a selection process at the level of the prime object will engage competition to direct attentional resources. In the absence of competition, only pop-out or pre-attentive processes are necessary to direct attention (Cave & Wolfe, 1990; Wolfe, 1994).

The data confirmed our prediction that OBA would be evident only in the orientation and color manipulations, and not in the motion manipulation. Orientation and color information are processed early in the ventral visual pathway cortical hierarchy (areas V1-V4), which is also relevant for complex object representations (inferotemporal cortex). Braddick, Birtles, Wattam-Bell, and Atkinson (2005) found orientation selectivity in young infants as early as 5 weeks of age. Johnson and Aslin (1996) found orientation to be a cue relevant to object unity as early as 4 months. Previous studies of infant chromatic vision showed that three types of cones (L, M, and S) are functional by 4 weeks of age (Knoblauch, Bieber, & Werner, 1998), and others have shown that infants' red/green channel (L–M cone pathway) is functional by 2 months (Bosworth & Dobkins, 2010; Dobkins, Anderson, & Kelly, 2001). However, infants do not use color for object individuation until around 11.5 months (Wilcox, 1999). Taken together, these studies are consistent with our findings that both younger and older infants engage OBA when object information is in competition with orientation information, whereas only older infants engage OBA when object information is in competition with color information.

In contrast to orientation and color information carried within the ventral visual pathway, the dorsal visual pathway carries motion information, which would not feed directly into cortical regions involved in object processing. Thus, we predicted that motion would not engage object-based attention at any age, which was supported by our findings. With respect to motion direction selectivity, Braddick et al. (2005) found that visual evoked potential responses become stronger between 5 and 18 weeks of age, with no evidence for motion selectivity before 8 weeks. Other work shows that the deployment of visual attention orienting in the context of face processing is not influenced by motion at 4 months of age (Valenza et al., 2015). Together, these sets of results are consistent with our finding that a feature-based attention effect for motion was stronger in older infants relative to younger infants.

An additional aim was to examine the relationship between OBA and SES, as indexed by family income. We found that when color competed with object information, greater income was associated with attentional priority and longer looking durations to the feature-match items in younger infants and to the object/form-match items in older infants. There are two possible interactive explanations for this result. First, income may shape this pathway as it relates to the number and variability of visual input through access to books, toys, and other complex visual stimuli (Bradley et al., 2001). Second, income may reflect differences in caregiver interactions during visual exploration, where caregivers may practice directing attention to one of several competing features of a complex object stimulus, thereby supporting attentional processes. Caregiver scaffolding has been shown to be an external guide to direct and switch attention (Bibok, Carpendale, & Müller, 2009) and is associated with adaptive development of executive functions in young children more broadly (Carlson, 2009; Hammond, Müller, Carpendale, Bibok, & Liebermann-Finestone, 2012). Note that our findings were linear across the SES spectrum and were not specific to the low-SES range (Amso & Lynn, 2017). This is an important point that shows that SES, here measured as family income, is indexing normative visual experiential differences in infants' environments. Future work will examine the mechanisms underlying these effects in detail.

Developmentally, OBA is intimately bound to object individuation, object perception, and even word learning. For instance, infants begin to individuate objects using both shape and size by 4–5 months of age, by using texture by 7–8 months of age, and by using color by 11–12 months of age (Wilcox, 1999). Perceptual completion in the service of object perception develops rapidly in the first several postnatal months (Amso & Johnson, 2006; Johnson, Amso, & Slemmer, 2003; Johnson & Slemmer, 2004) and is likely a precursor to OBA. For example, Johnson et al. (2003) habituated 3-month-old infants with a moving rod that was occluded by a box, and then tested whether infants perceived the rod as two broken parts or as a complete object. They found that where infants fixated during the habituation phase (top and bottom of the rod instead of the corners of the box) was related to whether they showed evidence of having a complete percept of the occluded object. Another line of work in older infants has linked word learning to a bias for object shape rather than some simultaneous competing feature. For example, if presented with a red ball, and the label "ball," the child's bias is to attach the label to the form of the object rather than to its color. This "shape bias" in word learning strengthens between 18 and 24 months and predicts rapid vocabulary growth (e.g., Gershkoff-stowe & Smith, 2004; Smith, Jones, Landau, Gershkoff-Stowe, & Samuelson, 2002). Taken together, these findings are consistent with our results showing a developmental shift from feature- to object-based attention, which interacts with the dimension of the feature that is in competition with whole-object information for attentional resources.

One interpretative limitation of this work is regarding the motion data. In our displays, the object/form-match was stationary, while the feature-match was moving. This design decision was necessary to address our primary question. It is possible that the strong bias for feature-based attention that we observed in the motion condition could reflect a visual pop-out effect (e.g., Abrams & Christ, 2003; Franconeri & Simons, 2003). However, when we examine looking times during the full duration of the test trials (2 s), we did not see a shift to the object/form-match at any point for either age group, which suggests that infants are not simply orienting based on visual pop-out. Moreover, this is also a tautological problem. If motion pops-out, then it is winning the competition with object/form information in the prime display as well. Nonetheless, future work will be necessary to determine whether there are any conditions under which object/form information can compete with motion for encoding. For instance, future work could consider having an object/form-match test item that also moves, but in a different fashion than the prime item. From an anatomical perspective, however, motion information is not processed in the same pathway as object information (dorsal visual pathway vs. ventral visual pathway, respectively). Thus, our result is predicted by the biology of the visual system. Indeed, it is intuitively rare that the motion of a stimulus is diagnostic of its objecthood. Rather, motion for object perception has been shown to be relevant to perceive parts of an object as continuous above and below an occluder (Johnson et al., 2003). In this instance, motion supports object perception through the Gestalt principle of common fate, rather than competing with the object shape for attentional resources.

In sum, our findings indicate that OBA develops over the first postnatal year and may depend on the feature that is in competition with whole-object information for attentional resources, as well as on normative visual experiential differences in infants' environments. The findings presented here increase our understanding of the development of OBA over the first year of life, and add new insights into how developmental changes in feature processing might increasingly impact OBA with development.

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