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OnlineFirst Version of Record - May 19, 2014

What is This?

Newly Hatched Chicks Solve the Visual Binding Problem

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Abstract

For an organism to perceive coherent and unified objects, its visual system must bind color and shape features into integrated color-shape representations in memory. However, the origins of this ability have not yet been established. To examine whether newborns can build an integrated representation of the first object they see, I raised newly hatched chicks (*Gallus gallus*) in controlled-rearing chambers that contained a single virtual object. This object rotated continuously, revealing a different color and shape combination on each of its two faces. Chicks were able to build an integrated representation of this object. For example, they reliably distinguished an object defined by a purple circle and yellow triangle from an object defined by a purple triangle and yellow circle. This result shows that newborns can begin binding color and shape features into integrated representations at the onset of their experience with visual objects.

Human adults build visual object representations that contain information about both the color and the shape of objects. Building these unified object representations requires that color and shape features be bound into integrated color-shape representations in memory. This is commonly called the *binding problem*. Many studies have examined how adults solve the visual binding problem (e.g., Brady, Konkle, Alvarez, & Oliva, 2013; Luck & Vogel, 1997; Treisman & Gelade, 1980; Urgolites & Wood, 2013; Wheeler & Treisman, 2002; Wolfe, 1994). So far, however, little is known about the origins of this ability. Can newborns build integrated representations of the first objects they see, or does this ability have a protracted developmental trajectory?

Because of the challenges associated with testing newborns experimentally, previous studies that examined visual binding abilities had to test infants days, weeks, or months after birth (e.g., Bhatt & Rovee-Collier, 1997; Bushnell & Roder, 1985; Slater, Mattock, Brown, Burnham, & Young, 1991; Taga et al., 2002). This limitation made it difficult to characterize the origins of visual binding abilities because the subjects' visual systems had already been shaped by their prior experiences with objects.

To determine whether newborns begin building integrated object representations at the onset of their experience with visual objects, it is necessary to study their very first object representation, before they have acquired any prior visual object experiences.

To study the nature of the first object representation built by a newborn organism, I used a *complete data* controlled-rearing method with a newborn animal model—the domestic chicken (Wood, 2013). I use the term *complete data* because the method involves recording all of the subjects' behavior (i.e., nine samples/s, 24 hr/day, 7 days/week). Chickens were used as the animal model for four reasons. First, newly hatched chicks have powerful object recognition abilities (e.g., Fontanari, Rugani, Regolin, & Vallortigara, 2011; Regolin & Vallortigara, 1995; Wood, 2013): For example, chicks can build a viewpoint-invariant representation of the first

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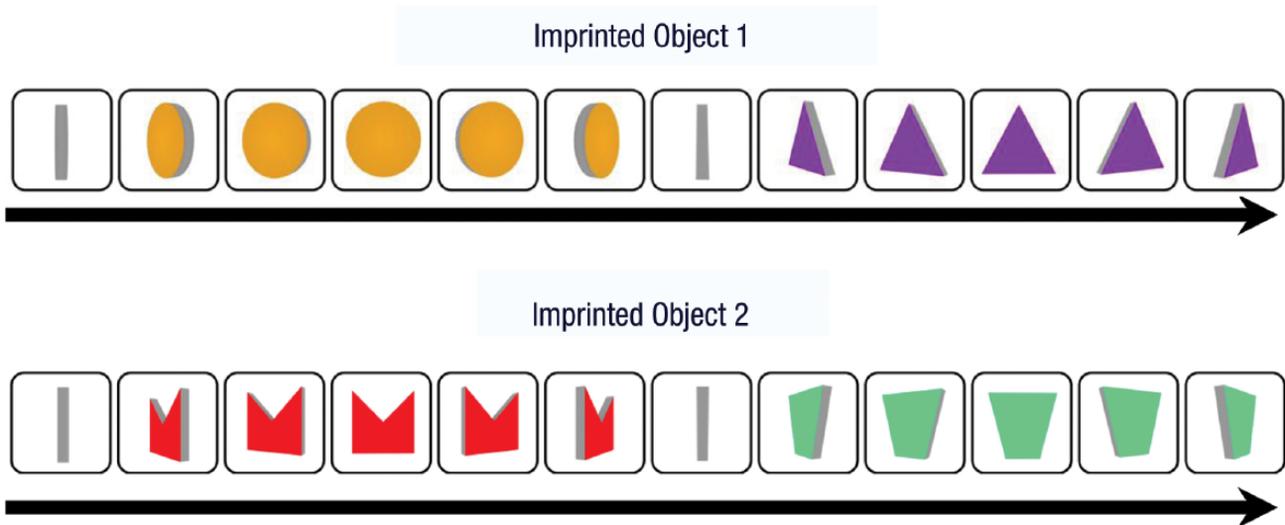E-mail: justin.wood@usc.edu

Fig. 1. Images from the two object animations presented during the input phase. Each object had two faces, and each face showed a different color and 3-D shape. The objects moved smoothly, completing a full rotation every 6 s (at 30 frames/s). The side edges of the two shapes looked identical, so the object changed smoothly from one 3-D shape to another. Each subject was shown only one of these animations.

object they see (Wood, 2013). This first viewpoint-invariant representation can be built from extremely sparse visual input (e.g., from an environment containing a single virtual object moving through a limited 60° viewpoint range). Second, newly hatched chicks can be raised in environments devoid of objects (Vallortigara, 2012; Wood, 2013). This makes it possible to control all of their visual object experiences after hatching. Third, chicks imprint to moving objects seen in the first few days of life (e.g., Bateson, 2000; Horn, 2004). This imprinting instinct provides a natural behavioral response that can be used to test object recognition abilities without training. Moreover, imprinting in chicks is subject to a critical period. Once the critical period ends, the chick can be presented with a large number of test trials without changing the imprinted representation (Wood, 2013). This allows each subject's first visual object representation to be measured with high precision. Fourth, chickens and primates use similar neural machinery to process sensory information. For instance, the basic cell types and connections of sensory input and output neurons are nearly identical (for a review, see Karten, 2013). This shared pattern of neural circuitry indicates that birds and primates use similar computations to build visual object representations. Together, these four characteristics make chickens an ideal (and unique) animal model for studying the origins of human object representation.

In the current study, newly hatched chicks were raised for 2 weeks within controlled-rearing chambers. These chambers tracked and recorded all of the subjects' behavior. In the 1st week of life (the input phase), each subject's visual object experience was limited to a single virtual object rotating around a single axis. The object rotated continuously, revealing a different color and shape on each of its two faces (Fig. 1). Using this type of geometrically impossible object allowed two different color-shape units to be presented on a single object. Thus, I was able to examine whether the first object representation built by the chick's visual system contained integrated color-shape units. In the 2nd week of life (the test phase), I measured the informational content of the object representation built by each chick. Specifically, I tested whether subjects built integrated representations that contained information about the specific configuration of color and shape features presented on the virtual object.

Method

Subjects

Ten domestic chickens (*Gallus gallus*) of unknown sex were tested. The sample size was determined before the experiment was conducted, and no subjects were excluded from the analyses. The eggs were obtained from a local distributor and incubated in darkness in an OVA-Easy incubator (Brinsea Products Inc., Titusville, FL). After hatching, the chicks were moved, in darkness, from the incubator to the controlled-rearing chambers. Each chick was raised within its own chamber. All care of the subjects was performed in darkness (night-vision goggles were used). The experiment was approved by the University of Southern California Institutional Animal Care and Use Committee.

Controlled-rearing chambers

The chambers measured 66 cm (length) × 42 cm (width) × 69 cm (height) and were constructed from white, high-density plastic. Food and water were available ad libitum within troughs in the ground that measured 66 cm (length) × 2.5 cm (width) × 2.7 cm (height). The troughs had transparent surfaces, so the food was never occluded from the subject. Grain was used as food because, unlike an object, it does not maintain a rigid, bounded shape. The floors of the chambers were black wire mesh supported over a black surface. For a picture of the controlled-rearing chambers, see Figure 1 in Wood (2013). Microcameras embedded in the ceilings of the chambers continuously tracked the subjects' movements.

Procedure

In the 1st week of life, subjects were raised in controlled-rearing chambers that contained a single virtual object. The object was shown on two display walls (19-in. LCD monitors with a screen size of 1,440 × 900 pixels) located on opposite sides of the chamber. The object appeared on one wall at a time, switching walls every 2 hr, after a 1-min period of darkness (Fig. 2a). The object had two faces, each with a different color and shape. The object rotated around a frontoparallel vertical axis (Fig. 1) and completed a full rotation every 6 s. The edges of the object shown during transitions from one face to the other looked identical. Thus, during its rotation, the object changed smoothly from one 3-D shape to another. On average, the object measured 9 cm (length) × 7 cm (height). It was displayed on a uniform white background. One group of subjects (*n* = 4) were imprinted to the object shown in the top row of Figure 1, and another group of subjects (*n* = 6) were imprinted to the object shown in the bottom row.

In the 2nd week of life, I used an automated two-alternative forced-choice testing procedure to examine whether subjects could recognize their imprinted objects across a variety of feature changes. During the test trials, two objects were shown simultaneously, one on each display wall (Fig. 2b), and I measured the amount of time subjects spent in proximity to each object. One object was the imprinted object from the input phase, and the other object was an unfamiliar object. If chicks can distinguish their imprinted object from an unfamiliar object, then they should spend a greater proportion of time in proximity to the imprinted object compared with the unfamiliar object. The chicks' movements were analyzed with automated tracking software (EthoVision XT, Noldus Information Technology, Leesburg, VA) that calculated the amount of time subjects spent within two 22- × 42-cm zones, one next to each of the display walls.

During the test trials, the unfamiliar object could differ from the imprinted object in seven different ways:

- *Color-change conditions:* In these two conditions, the imprinted object was paired with an unfamiliar object that was identical to the imprinted object except that one or both colors were replaced with novel colors.
- *Shape-change conditions:* In these two conditions, the imprinted object was paired with an unfamiliar object that was identical to the imprinted object except that one or both shapes were replaced with novel shapes.
- *Color-shape-change conditions:* In these two conditions, the imprinted object was paired with an unfamiliar object in which one face was replaced with a novel color and shape or both faces were replaced with novel colors and shapes.
- *Binding-change condition:* The imprinted object was paired with an unfamiliar object that had the same color and shape features as the imprinted object, but in a different configuration (e.g., a yellow triangle and a purple circle vs. a yellow circle and a purple triangle).

During the test phase, subjects received 168 test trials (1 per hour). Each test trial lasted 20 min and was followed by a 40-min rest period. During the rest periods, the animation from the input phase was shown on one display wall, and the other display wall was blank (Fig. 2b).

Results

Test trials were scored as "correct" when subjects spent a greater proportion of time with the imprinted object than with the unfamiliar object and "incorrect" when they spent a greater proportion of time with the unfamiliar object than with the imprinted object. These scores were analyzed using hierarchical Bayesian methods that provided detailed probabilistic estimates of recognition performance for the individual subjects and the entire sample (Kruschke, 2011).

The Bayesian analysis first required specification of a prior distribution. To be conservative, I used a prior distribution consisting of one correct trial and one incorrect trial. The prior distribution also included a kappa parameter that represented the consistency across subjects. I used a uniform density value for kappa (Gelman, 2006) that ranged from 0.000001 (i.e., very little consistency across subjects) to a reasonable maximum, which was estimated from subjects' performance during the
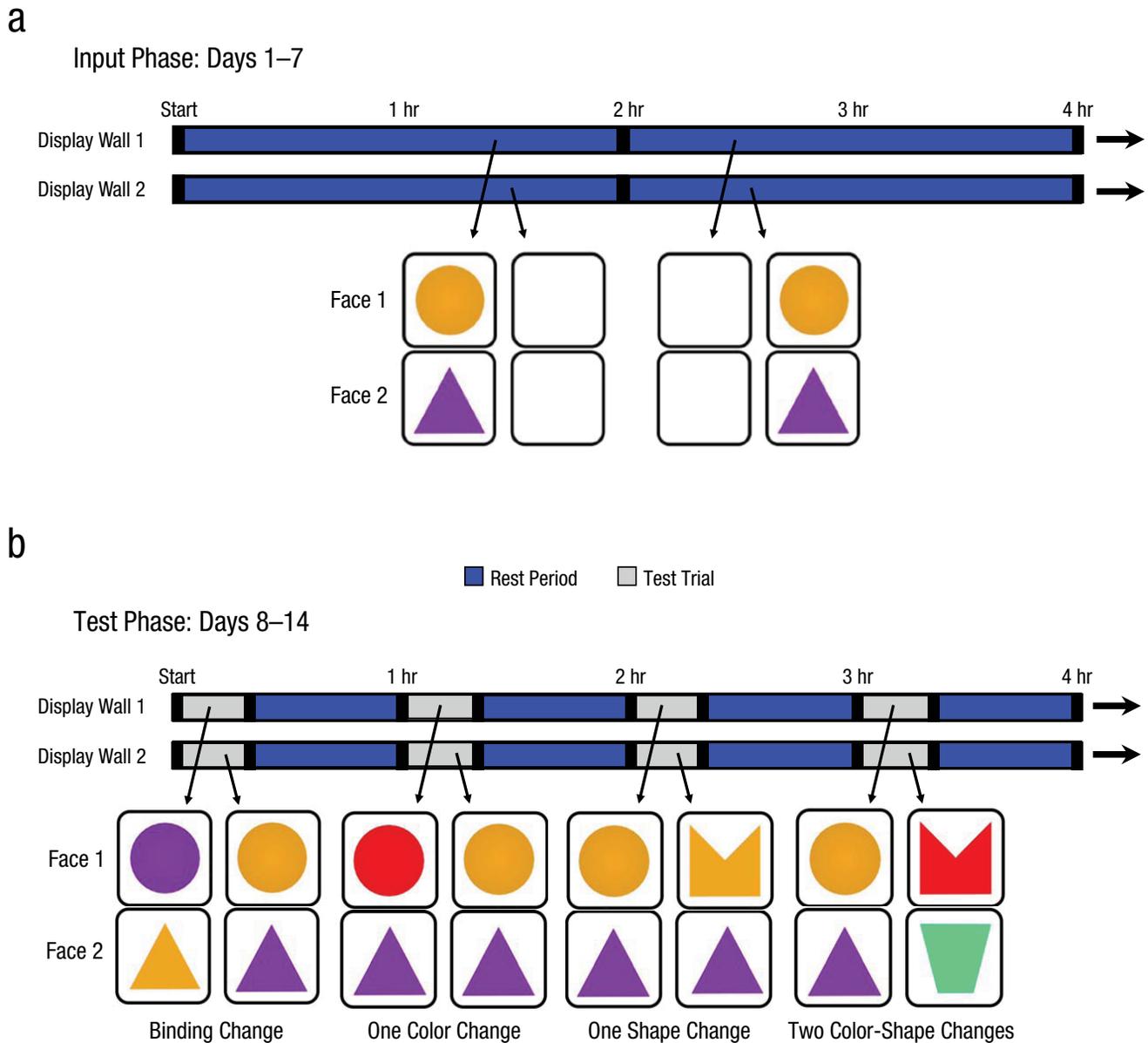
a

Input Phase: Days 1–7

b

Test Phase: Days 8–14

Fig. 2. An illustration of the experimental design. These schematics show how the virtual stimuli were presented for sample 4-hr periods during the (a) input phase and (b) test phase. During the input phase, a single virtual object appeared on one wall at a time (indicated by blue segments on the timeline), switching walls every 2 hr, after a 1-min period of darkness (black segments). During the test phase, two virtual objects (one imprinted, the other unfamiliar) were shown simultaneously, one on each display wall, for 20 min per hour (gray segments). The illustrations below the timeline are examples of paired test objects displayed in four of the conditions. Each test trial was followed by a 40-min rest period (blue segments). During the rest periods, the animation from the input phase was shown on one display wall, and the other display wall was blank. These illustrations show the displays seen by subjects that were imprinted to Imprinted Object 1 (Fig. 1).

rest periods in the test phase. The rest periods were expected to produce the greatest consistency across subjects because they presented the easiest choice (i.e., subjects chose whether to spend time with their imprinted object as opposed to a white screen). The Bayesian analysis used Markov-chain Monte Carlo sampling to estimate the probability that performance was above chance level.

Figure 3a shows subjects' average performance across the conditions. In the color-change conditions, subjects successfully distinguished their imprinted object from the unfamiliar objects on 80% (*SEM* = 4) of the test trials. The probability that group performance was above chance was greater than 99.9%. The probability that individual performance was above chance was 99% or greater for 9 of the subjects and 91% for the remaining subject. The
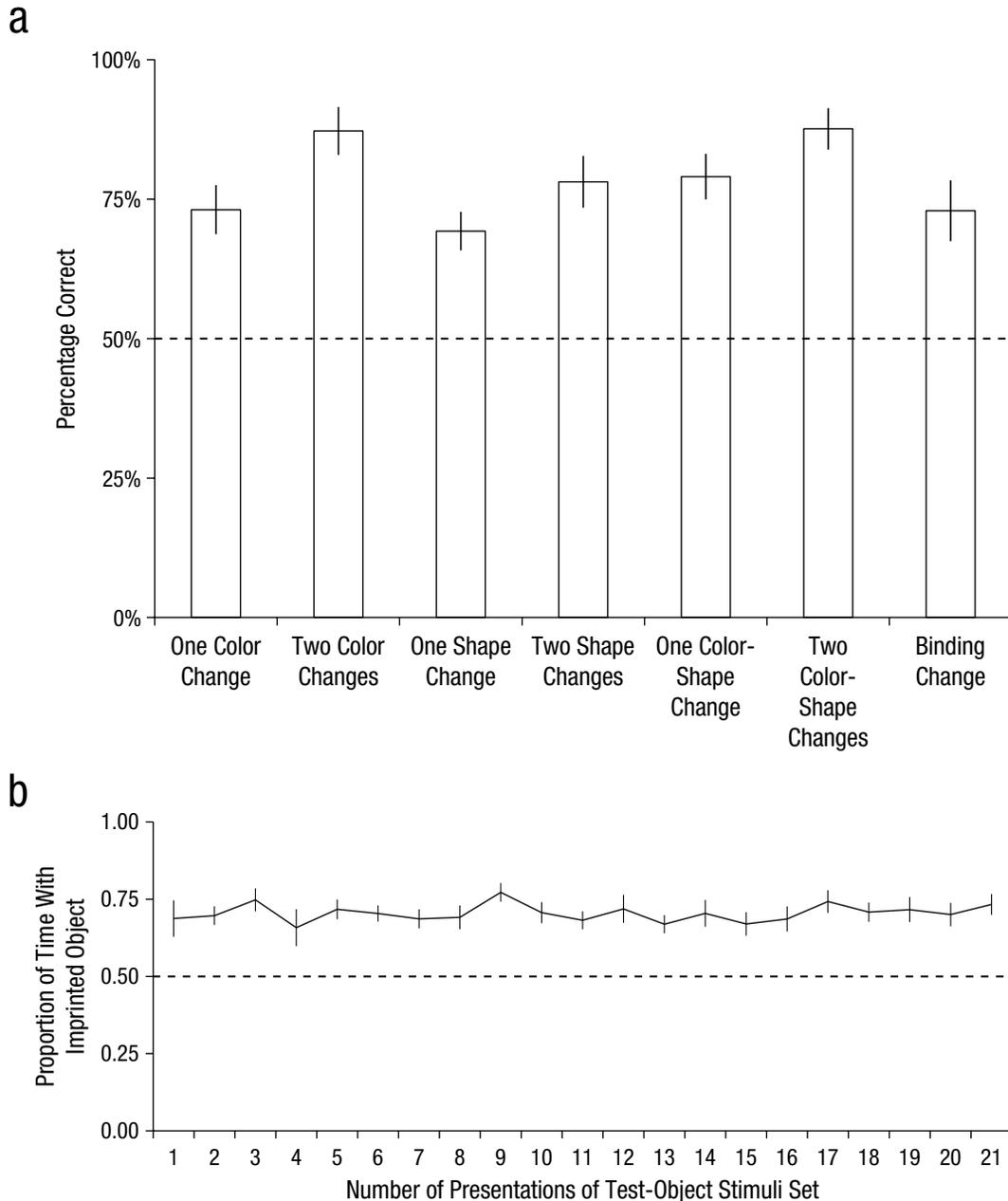
a

b

Fig. 3. Results from the test phase. The bar graph (a) shows the mean percentage of trials scored as correct as a function of condition. The line graph (b) shows the group mean proportion of time that subjects spent with the imprinted object rather than with the unfamiliar object as a function of the number of presentations of the test objects. Error bars denote ±1 *SE*. Chance performance (dashed lines) was 50%.

probability that group performance was above chance was greater than 99.9% both when there was a color change on one face of the imprinted object and when there was a color change on both faces of the object.

In the shape-change conditions, subjects successfully distinguished their imprinted object from the unfamiliar objects on 74% (*SEM* = 4) of the test trials. The probability that group performance was above chance was greater than 99.9%. The probability that individual

performance was above chance was 99% or greater for 9 of the subjects and 95% for the remaining subject. The probability that group performance was above chance was greater than 99.9% both when there was a shape change on one face of the imprinted object and when there was a shape change on both faces of the object.

In the color-shape-change conditions, subjects successfully distinguished their imprinted object from the unfamiliar objects on 83% (*SEM* = 4) of the test trials.

The probability that group performance was above chance was greater than 99.9%. The probability that individual performance was above chance was 99% or greater for 9 of the subjects and 98% for the remaining subject. The probability that group performance was above chance was greater than 99.9% both when there was a color and shape change on one face of the imprinted object and when there was a color and shape change on both faces of the object.

Finally, in the binding-change condition, subjects successfully distinguished their imprinted object from the unfamiliar object on 73% (*SEM* = 6) of the test trials. The probability that group performance was above chance was greater than 99.9%. The probability that individual performance was above chance was 99% or greater for 8 of the subjects, above 93% for 1 subject, and below 50% for the remaining subject.

Overall, subjects were able to recognize their imprinted object with high precision across the seven conditions (Fig. 3a). The same general pattern was observed for both imprinted objects.

Next, I examined whether performance changed over the course of the test phase by analyzing the proportion of time subjects spent in proximity to their imprinted object as a function of the number of times the test objects had been presented (i.e., first presentation, second presentation, etc.). Performance was high and significantly above chance even for the first presentation of the test objects, $t(9) = 3.19$, $p = .01$, and remained stable over the course of the test phase (Fig. 3b), with little variation as a function of number of presentations, $F(20, 209) = 0.53$, $p = .95$. Thus, subjects' recognition behavior was spontaneous and robust, and their high level of performance cannot be explained by learning across the test phase. Subjects immediately achieved their maximal performance and did not improve significantly thereafter.

Discussion

This study examined whether newborns can build an integrated representation of the first object they see. Specifically, newly hatched chicks raised in controlled-rearing chambers that contained a single virtual object were able to build an integrated representation of the object, binding its color and shape features into integrated color-shape representations in memory. This result suggests that visual binding abilities are present and functional at the onset of visual object experience.

Although subjects were raised in an environment that contained a single object, they received extensive experience with that object (during the 1-week input phase). Thus, additional research is needed to determine whether newborns can build an integrated object representation

after seeing an object briefly, as can human adults (e.g., Wheeler & Treisman, 2002), or instead require prolonged exposure to the object.

More generally, these results complement my recent study showing that newly hatched chicks can build a viewpoint-invariant representation of the first object they see (Wood, 2013). Like adult primates, newly hatched chicks build invariant object representations that generalize far beyond the visual input used to build those representations. Together, these two studies show that newborns' visual systems are surprisingly powerful: At the onset of visual object experience, newborns can build both invariant and integrated object representations.

Author Contributions

J. N. Wood is the sole author of this article and is responsible for its content.

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