SHORT REPORT

Measuring the speed of newborn object recognition in controlled visual worlds

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Abstract

How long does it take for a newborn to recognize an object? Adults can recognize objects rapidly, but measuring object recognition speed in newborns has not previously been possible. Here we introduce an automated controlled-rearing method for measuring the speed of newborn object recognition in controlled visual worlds. We raised newborn chicks (Gallus gallus) in strictly controlled environments that contained no objects other than a single virtual object, and then measured the speed at which the chicks could recognize that object from familiar and novel viewpoints. The chicks were able to recognize the object rapidly, at presentation rates of 125 ms per image. Further, recognition speed was equally fast whether the object was presented from familiar viewpoints or novel viewpoints (30° and 60° azimuth rotations). Thus, newborn chicks can recognize objects across novel viewpoints within a fraction of a second. These results demonstrate that newborns are capable of both rapid and invariant object recognition at the onset of vision.

Research highlights

- We introduce a controlled-rearing method for measuring the speed of newborn object recognition in controlled visual worlds.
- After being raised in an environment containing a single virtual object, newborn chicks could recognize the object rapidly (within 125 ms).
- Recognition speed was equally fast whether the object was presented from familiar or novel viewpoints.
- These results demonstrate that newborns are capable of both rapid and invariant object recognition.

Introduction

One of the most remarkable features of adult visual systems is the speed at which object recognition takes place. We can effortlessly recognize objects from among tens of thousands of possibilities, all within a fraction of a second (Intraub, 1980; Keysers, Xiao, Foldiak & Perrett, 2001; Potter, 1976; Rousselet, Fabre-Thorpe & Thorpe, 2002). For instance, human adults can recognize objects presented sequentially at rates less than ~100 ms per image (Potter, 1976; Potter, Wyble, Hagmann & McCourt, 2014), and studies measuring event-related potentials find neural signatures reflecting object categorization within 150 ms (Thorpe, Fize & Marlot, 1996).

What are the origins of such rapid visual processing? Does this ability emerge late in life, or can newborns recognize objects rapidly at the onset of vision? Due to the difficulties associated with testing newborn subjects experimentally, it has not previously been possible to measure the speed of object recognition in a newborn visual system. Three major barriers have hindered progress. First, it is typically possible to collect just a few test trials from newborn subjects, which has prevented detailed chronometric measurement of early emerging visual processes. Second, newborn humans cannot be raised in strictly controlled environments from birth, which has prevented examination of whether extensive visual experience is needed for the development of rapid object recognition abilities. Third, newborns have slow and restricted motor repertoires. Thus, measures such as reaction time will primarily reflect the time

required to perform an action during response execution rather than the viewing time required for object recognition.

Here we describe an automated controlled-rearing method that overcomes these three barriers. The method allowed us to measure the speed of object recognition in a newborn animal – the domestic chick (*Gallus gallus*). We used newborn chicks as an animal model because they are an ideal model system for studying the development of vision. First, newborn chicks can begin building invariant object representations at the onset of vision (Wood, 2013; Wood & Wood, 2015). These abstract representations can be created from sparse visual input (e.g. from a world containing a single virtual object rotating through a limited 60° viewpoint range). The present study extends this work by examining whether newborn chicks can recognize objects rapidly. Critically, with chicks, it is possible to examine the speed of object recognition after a newborn subject has built their first visual object representation. Second, chicks are a highly precocial species and can be raised in strictly controlled environments immediately after hatching (Vallortigara, 2012; Versace & Vallortigara, 2015). Finally, avian and mammalian brains contain homologous cortical circuits for processing sensory input (Karten, 2013). Although these circuits are organized differently in birds and mammals (nuclear vs. layered organization, respectively), the circuits share similarities in terms of cell morphology, the connectivity pattern of the input and output neurons, gene expression, and function (Calabrese & Woolley, 2015; Dugas-Ford, Rowell & Ragsdale, 2012; Jarvis, Gunturkun, Bruce, Csillag, Karten et al., 2005; Wang, Brzozowska-Prechtl & Karten, 2010). There is also evidence that birds and mammals develop similar capacities for representing number, space, physical causality, and agency (reviewed by Vallortigara, 2012; Haun, Jordan, Vallortigara & Clayton, 2010). Since birds and mammals use similar mechanisms to perceive and understand the world, controlled-rearing studies of newborn chicks can inform the development of vision in humans.

In the first week of life, we raised newborn chicks in strictly controlled environments that contained no objects other than a single virtual object. In the second week of life, we measured the speed at which the chicks could recognize that virtual object. The controlled-rearing chambers tracked all of the chicks' behavior (24/7) for two weeks, which allowed us to collect over 100 test trials from each subject. Thus, we were able to obtain accurate measurements of each chick's object recognition speed. In addition, we measured object recognition speed not by focusing on reaction times, but by varying the amount of time available for constructing a representation of the object. Consequently, our approach did not require that the newborn subjects be capable of performing rapid motor movements (for a related approach used to study the speed of numerical cognition in human infants, see Wood & Spelke, 2005).

Importantly, researchers have measured the speed of object recognition in two distinct ways (Keysers et al., 2001). Some researchers (e.g. Thorpe et al., 1996) have measured the amount of time needed for neural signals to propagate to object recognition areas of the brain after an object has been seen. Other researchers (e.g. Potter, 1976; Potter et al., 2014) have measured the amount of time an object must be visible in order for the object to be recognized. Here we used the latter approach, testing the minimal amount of time an object must be visible for a newborn chick to recognize the object.

Across two experiments, we examined whether newborn chicks are capable of rapid and invariant object recognition. Specifically, we measured object recognition speed across both familiar and novel viewpoints (30° and 60° azimuth rotations). Thus, our experiment simultaneously tested whether two core characteristics of adult object recognition – rapid and invariant recognition – can be present in newborn visual systems.

Experiment 1

Method

Subjects

Eleven domestic chicks of unknown sex were tested. The sample size was determined before the experiments were conducted, based on previous automated controlled-rearing experiments with newborn chicks (e.g. Wood, 2013, 2014). 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). The incubation room was kept in complete darkness. After hatching, the chicks were moved from the incubation room to the controlled-rearing chambers in darkness with the aid of night vision goggles. Each chick was raised singly within its own chamber. This research was approved by the University of Southern California Institutional Animal Care and Use Committee.

Procedure

We raised newborn chicks for two weeks within specially designed controlled-rearing chambers, which measured 66 cm (length) × 42 cm (width) × 69 cm (height). These

chambers provided complete control over all visual object experiences. Specifically, the chambers were devoid of all real-world (solid, bounded) objects. To present object stimuli to the chicks, we projected virtual three-dimensional objects on two display walls (19″ LCD monitors with 1440 × 900 pixel resolution) situated on opposite sides of the chamber. Food and water were provided within transparent troughs in the ground that measured 66 cm (length) × 2.5 cm (width) × 2.7 cm (height). Grain was used as food because a heap of grain does not behave like an object (i.e. a heap of grain does not maintain a rigid, bounded shape). The floors of the chambers were black wire mesh suspended over a black surface.

The chambers recorded all of the chicks' behavior (9 samples/second, 24 hours/day, 7 days/week) via micro-cameras in the ceilings and automated image-based tracking software (EthoVision XT, Noldus Information Technology, Leesburg, VA). This high-throughput data collection approach made it possible to collect a large

number of test trials (140 trials) from each chick and, consequently, measure each newborn subject's object recognition abilities with high precision. In total, 7728 hours of video footage (14 days × 24 hours/day × 23 subjects) were collected across Experiments 1 and 2.

In the 1st week of life (the input phase), chicks were raised in environments that contained a single virtual object rotating around a frontoparallel horizontal axis (Figure 1A, Video S1). The object moved smoothly (24 frames/second), completing a full rotation every 15 seconds. On average, the virtual object measured 8 cm (length) × 7 cm (height) and was suspended 3 cm off the ground. The object was displayed in the middle of the display wall on a uniform white background. The object appeared for an equal amount of time on the left and right display walls, switching walls every 2 hours (Figure 2B). This virtual object made up the entirety of the chick's visual object experience: the subjects never observed any other objects during the input phase. Based on previous research, we
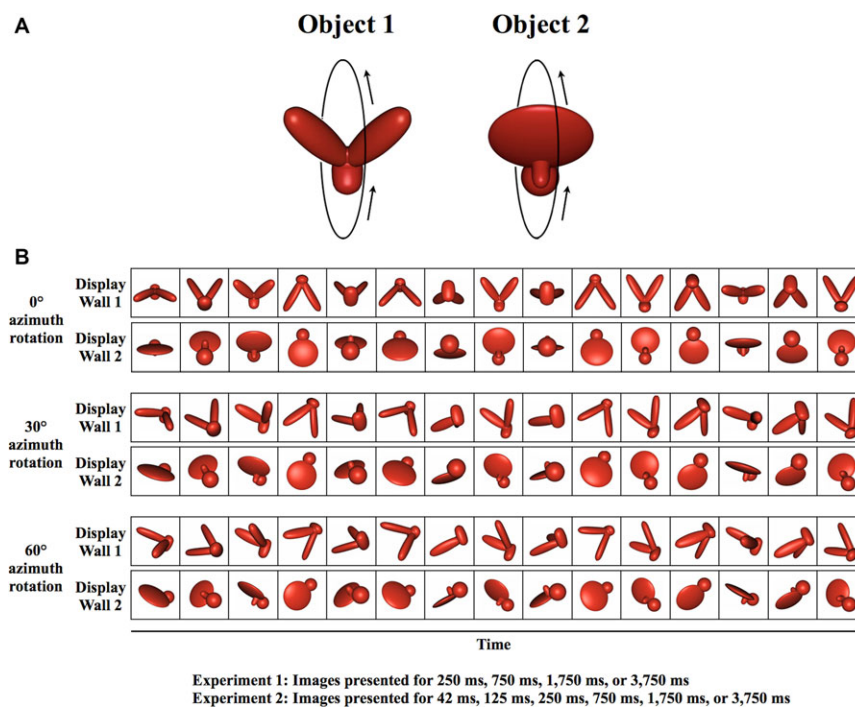

Figure 1 *Stimuli. (A) In the first week of life (input phase), newborn chicks were raised with a single virtual object rotating around a single axis. The chicks were imprinted to either Object 1 or Object 2. (B) In the second week of life (test phase), we used an automated two-alternative testing procedure to examine whether the chicks could recognize the imprinted object from the input phase. During the test trials, we projected successive images of the imprinted object on one display wall and successive images of an unfamiliar object on the other display wall. Across different test trials, the chicks were tested on all combinations of four presentation speeds (250 ms, 750 ms, 1750 ms, 3750 ms) and three azimuth rotation changes (0°, ±30°, ±60°). In Experiment 2, we tested the chicks on two additional presentation speeds (42 ms and 125 ms), and the unfamiliar object was presented from the same azimuth rotation as the imprinted object in the input phase.*
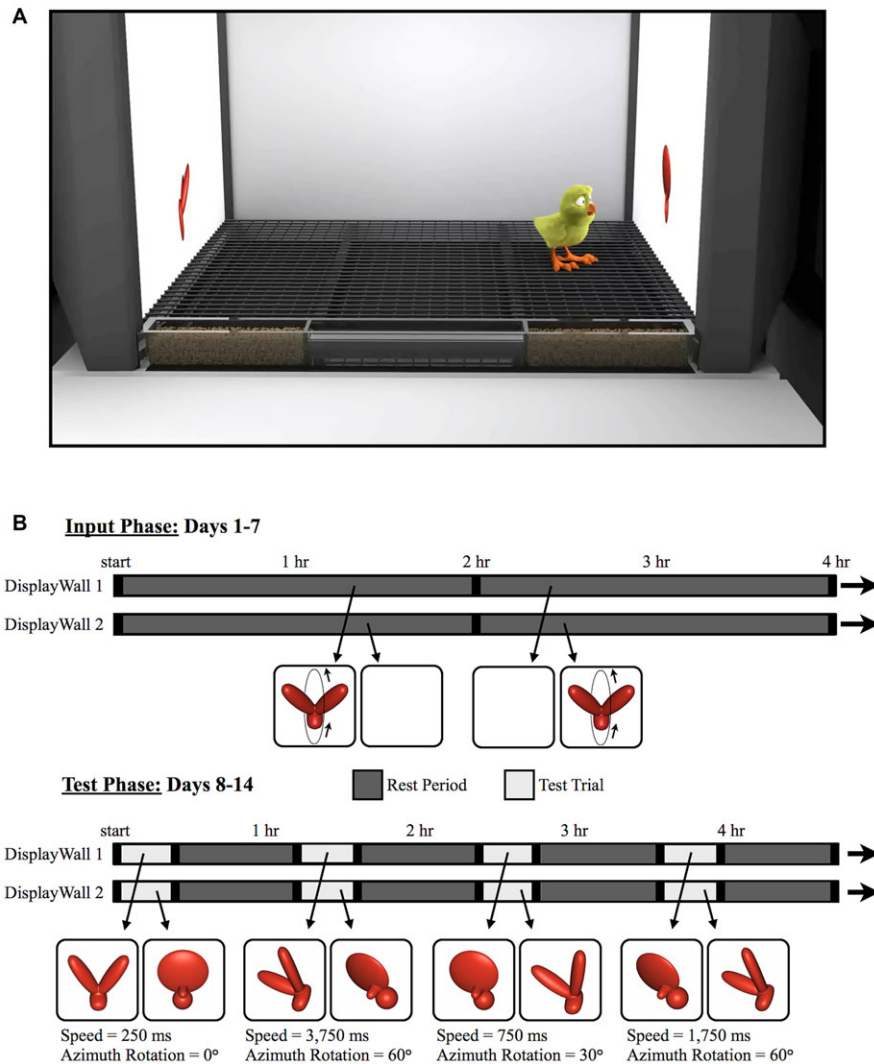
Figure 2   *(A) Illustration of a controlled-rearing chamber. The chambers contained no real-world (rigid, bounded) objects. To present object stimuli to the chicks, we projected virtual objects on two display walls (LCD monitors) situated on opposite sides of the chamber. For photographs of a controlled-rearing chamber, see Figure 1 in Wood (2013). (B) The schematic shows how the virtual objects were presented on the display walls during a period in the input phase and test phase. During the test trials, different views of the objects were presented sequentially at a constant presentation rate. The different sequential views had the same azimuth rotation and different elevation rotations.*

expected chicks to imprint to this virtual object (Wood, 2013). The chicks were imprinted to one of the two virtual objects shown in Figure 1. Five of the chicks were imprinted to Object 1, with Object 2 serving as the unfamiliar object, and six of the chicks were imprinted to Object 2, with Object 1 serving as the unfamiliar object. The virtual objects were modeled after those used in previous studies that tested for invariant object recognition in adult rats (Zoccolan, Oertelt, DiCarlo & Cox, 2009) and newborn chicks (Wood, 2013, 2015).

In the 2nd week of life (the test phase), we used an automated two-alternative testing procedure to examine whether the chicks could recognize the imprinted object across familiar and novel viewpoints. During the test trials, successive images of the imprinted object were shown on one display wall, and successive images of an unfamiliar object were shown on the other display wall (Figure 1B, Video S2). If the chicks could recognize the imprinted object on a test trial, then they should have spent more time with the imprinted object compared to the unfamiliar object.

To test whether newborn chicks are capable of recognizing objects rapidly across novel viewpoints, we manipulated the presentation speed of the successive object images and the viewpoint of the objects. Across the test trials, we tested chicks on all possible combinations of four presentation speeds (the object images were presented for 250 ms, 750 ms, 1750 ms, or 3750 ms) and three viewpoint changes (0°, ±30°, ±60° azimuth rotations). To make each image more distinct and to eliminate apparent motion, we (a) included a 250-ms blank display between each image[1] (thus, the stimulus onset asynchronies (SOAs) were 500 ms, 1000 ms, 2000 ms, or 4000 ms across the four presentation speeds) and (b) ensured that the successive viewpoints of the objects differed considerably from one another in terms of their elevation rotation. The same set of 15 uniformly spaced viewpoints was used across the four presentation speeds. These 15 viewpoints were presented in a scrambled order; on average, the successive views differed by 131.2° and the minimum difference between two successive views was 96° (elevation rotation). The imprinted object and unfamiliar object were presented from the same viewpoint range (Figure 1B). The animations from the 750-ms presentation speed are shown in Video S2.

The chicks received 20 test trials per day. Each test trial lasted 24 minutes, and was followed by a 48-minute rest period (Figure 2B). During each rest period, the input animation from the input phase appeared on one display wall and a white screen appeared on the other display wall. The chicks' movements were analyzed with automated tracking software that calculated the amount of time the chick spent within zones (22 cm × 42 cm) located next to each test object. We performed all animal husbandry in darkness with night vision goggles to avoid exposing the chicks to any extraneous visual input.

Results

Recognition performance

To compute each chick's object recognition performance, we computed the percent of time each chick spent with the imprinted object compared to the unfamiliar object (a) for trials where the imprinted object switched display walls after the rest period and (b) for the trials where the imprinted object stayed on the same display wall after the rest period. Then we computed the average of these two values to obtain a single recognition performance score for each chick in the condition.[2]

The results are shown in Figure 3A. The chicks' object recognition performance was significantly above chance levels for all presentation speeds (one-tailed t-tests; 250 ms: $t(10) = 4.13$, $p = .001$; 750 ms: $t(10) = 2.92$, $p = .008$; 1750 ms: $t(10) = 3.05$, $p = .006$; 3,750 ms: $t(10) = 4.64$, $p < .001$) and viewpoint changes (0° azimuth rotation: $t(10) = 5.09$, $p < .001$; ±30° azimuth rotation: $t(10) = 3.05$, $p = .006$; ±60° azimuth rotation: $t(10) = 3.19$, $p = .005$). A 3 × 4 repeated-measures ANOVA with Viewpoint Change and Presentation Speed as within-subject factors did not reveal any significant main effects or interactions (all ps > .20). Thus, the chicks' object recognition performance did not vary as a function of either the magnitude of the viewpoint change or the speed at which the objects were presented within the displays. The effect sizes (Cohen's d) for the four presentation speeds were as follows: 250 ms = 1.24; 750 ms = .88; 1750 ms = .92; 3750 ms = 1.40. The effect sizes for the three viewpoint changes were as follows: 0° azimuth rotation = 1.53; ±30° azimuth rotation = .92; ±60° azimuth rotation = .96.

To test whether the chicks' object recognition performance changed over the course of the test phase, we analyzed the proportion of time the chicks spent in proximity to the imprinted object versus the unfamiliar object as a function of test trial number. Performance remained stable over the course of the test phase (Figure 3C) with little variation as a function of test trial number (one-way repeated measures ANOVA, $F(6, 60) = .588$, $p = .739$). Further, performance was high and significantly above chance levels even for the first presentation of the test stimuli (one-tailed t-test, $t(10) = 3.247$, $p = .004$, Cohen's $d = .98$). Performance, measured on a minute-by-minute basis, was also stable across the first test trial (one-way repeated measures ANOVA, $F(23, 230) = 1.291$, $p = .174$). The chicks' recognition behavior was spontaneous and robust and cannot be explained by learning taking place across the test phase.

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[1] Since chickens have a relatively high flicker fusion rate (~100 Hz), this 250-ms gap between images was likely sufficient to prevent the chicks from fusing the successive images into a single percept.
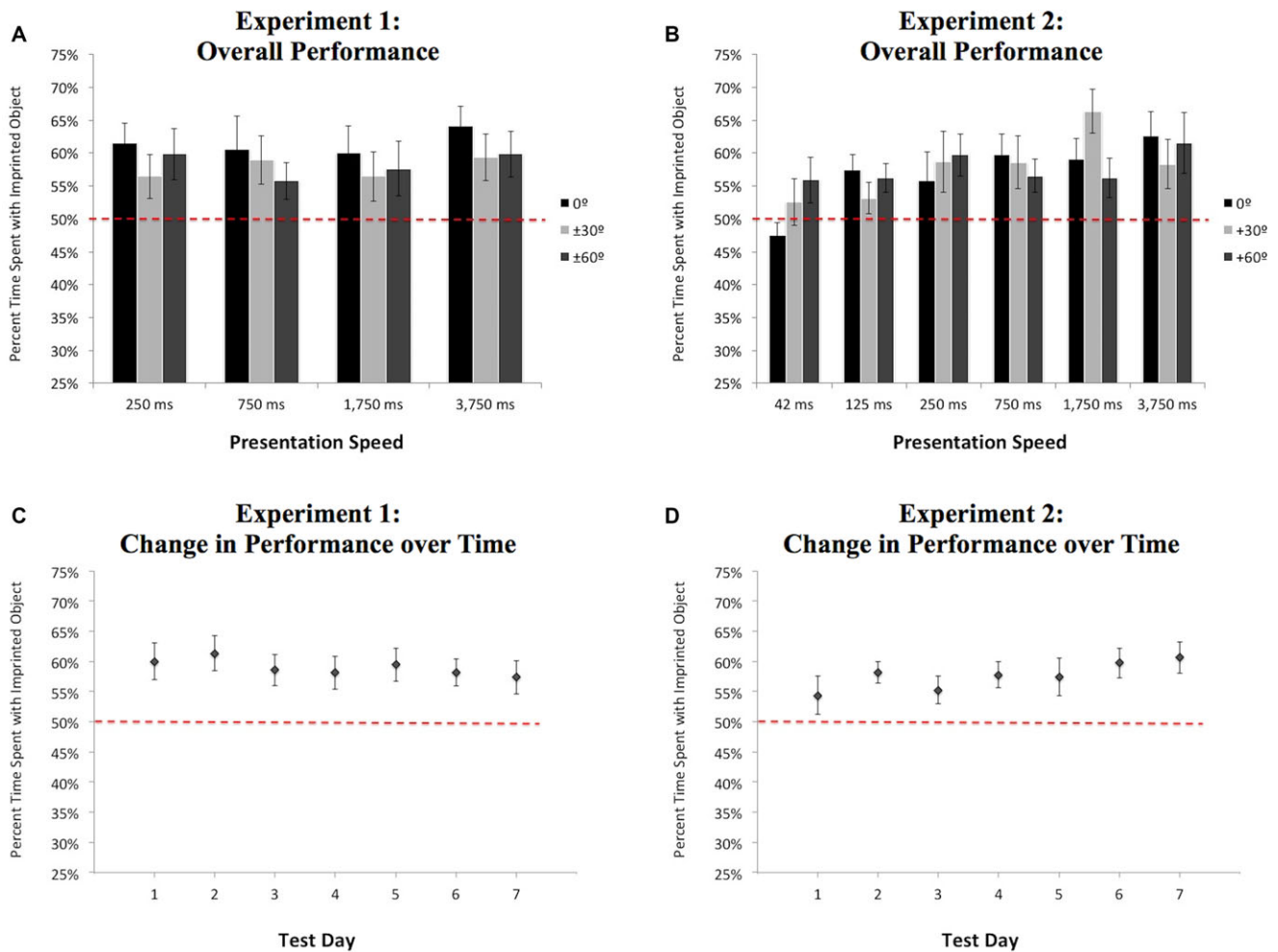
[2] We computed the average of these two values because performance was significantly higher on the test trials where the imprinted object stayed on the same display wall after the rest period compared to the test trials where the imprinted object switched display walls after the rest period. This is a natural consequence of tracking all of the chicks' behavior because if the chick was sleeping, feeding, or resting when the experiment switched from a rest period to a test trial, then they would remain on the 'correct' side of the chamber on some trials and the 'incorrect' side of the chamber on other trials, without having made a choice between the two objects. Computing the average of these two values corrected for this issue.

Figure 3   *Results. The top graphs show the chicks' mean object recognition performance across the presentation speeds and viewpoint changes for (A) Experiment 1 and (B) Experiment 2. The bottom graphs show the chicks' mean object recognition performance across the test phase for (C) Experiment 1 and (D) Experiment 2, computed for the first, second, third, etc., day of testing. Error bars denote ±1 SE. Chance performance (dashed lines) was 50%.*

Analysis of object stimuli

To investigate whether chicks needed invariant object representations to succeed in this task, we quantified the similarity between the input animations and test animations in two ways. First, we measured the overall brightness of each animation by computing the sum of the pixel intensities for each frame in each animation. As shown in Figure 4A, the test animations of the imprinted object were more similar to the input animations than the test animations of the unfamiliar object were to the input animations. Thus, in principle, the chicks could have used overall brightness as a low-level cue to distinguish between these objects. We control for this confound in Experiment 2 described below.

Second, we computed the amount of image variation between the input animations and test animations from a V1-level perspective. To compute V1-level similarity, we used a Gabor measure of similarity with the Gabor jet model: a multi-scale, multi-orientation model of V1 complex-cell filtering developed by Lades, Vorbruggen, Buhmann, Lange, Vandermalsburg *et al.* (1993). For each unique image in each animation, we measured the magnitude of activation values that the image produced in a set of 40 Gabor jets (8 orientations × 5 scales). We measured the dissimilarity between two images by computing the Euclidean distance between their Gabor jet activation values. Finally, we calculated the average Gabor jet dissimilarity across all unique images of the animations, comparing each image in the test animation to each image in the input animation. As shown in Figure 4C, the between-object image difference (i.e. the V1-level difference between the test animation of the
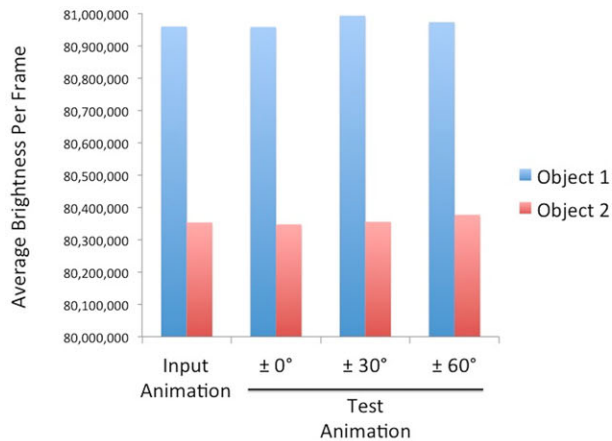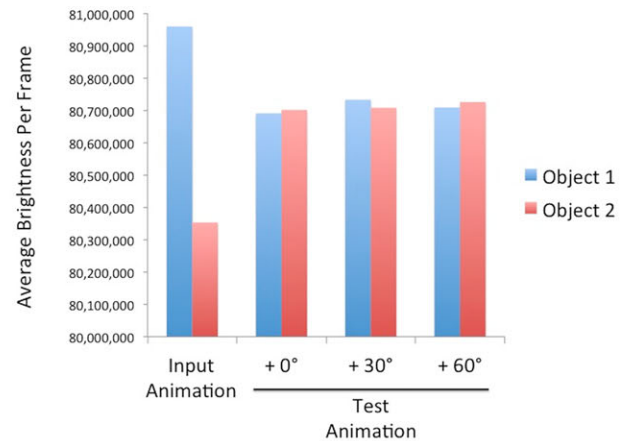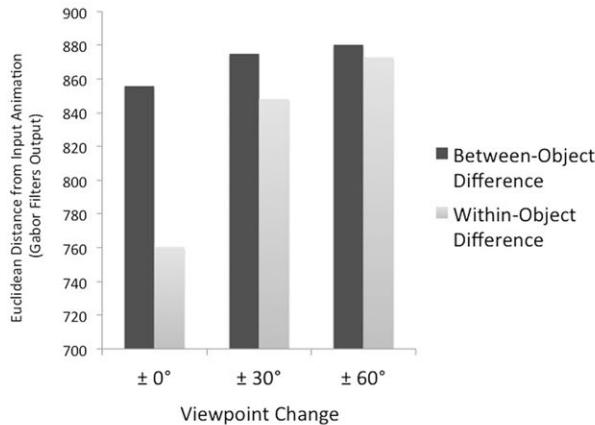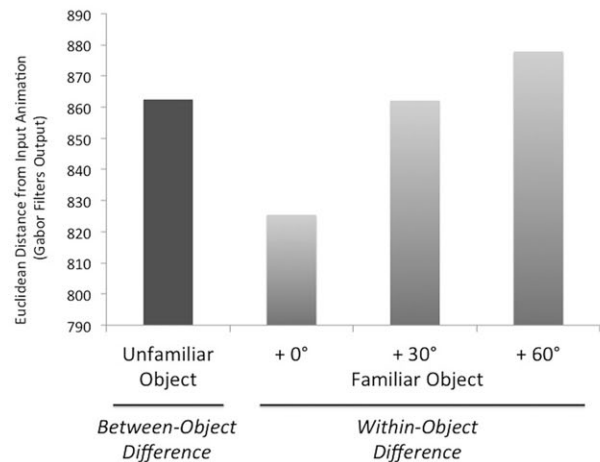
Figure 4 *Results of the analyses of the virtual objects. The top graphs show the overall brightness levels of the objects from (A) Experiment 1 and (B) Experiment 2. Since the test objects had similar brightness values in Experiment 2, the chicks could not have used overall brightness as a low-level cue to recognize their imprinted object. The bottom graphs show the V1-level similarity between the input objects and test objects for (C) Experiment 1 and (D) Experiment 2. Since V1-level similarity was not predictive of object identity across the azimuth rotation changes in Experiment 2, the chicks could not have used V1-level similarity as a low-level cue to recognize their imprinted object.*

unfamiliar object and the input animation of the imprinted object) was greater than the within-object image difference (i.e. the V1-level difference between the test animation of the imprinted object and the input animation of the imprinted object) for all viewpoint changes. Thus, in principle, chicks could have used V1-level image difference as a low-level cue to distinguish between these objects. We control for this confound in Experiment 2 described below.

Discussion

These results provide suggestive evidence that newborn chicks are capable of rapid and invariant object recognition. There are, however, at least three alternative explanations for this finding. First, when we compared the overall brightness of the test animations and input animations (Figure 4A), the test animations of the imprinted object were more similar to the input animations than the test animations of the unfamiliar object

were to the input animations. Thus, the chicks might have used brightness as a low-level cue to recognize their imprinted object. Second, when we compared the V1-level similarity between the test animations and input animations using a bank of Gabor filters (Figure 4C), the between-object image difference was greater than the within-object image difference. Thus, the chicks might have recognized their imprinted object by relying on low-level V1-like features, rather than building viewpoint-invariant object representations. Third, the chicks' recognition performance did not vary as a function of the presentation speed of the images: performance was nearly identical for the fastest (250 ms) and slowest (3750 ms) presentation speeds: $t(10) = 1.049$, $p = .319$, Cohen's $d = .32$. The lack of an effect for presentation speed raises the possibility that this method is unsuitable for measuring the speed of object recognition in newborn chicks.

To test these alternative explanations, we performed a second experiment in which we (1) controlled for the overall brightness of the imprinted object and unfamiliar object during the test trials (Figure 4B), (2) controlled for the V1-level between-object and within-object image difference (Figure 4D), and (3) added two faster presentation speeds to the design (42 ms and 125 ms).

Experiment 2

Method

Twelve new chicks were tested in this experiment. The methods were identical to those used in Experiment 1 except for the following changes. First, to control for the brightness of the objects, we equated the overall brightness of the imprinted object and unfamiliar object on the test trials by increasing the size of the images of Object 1 by 10% and decreasing the size of the images of Object 2 by 10% (Figure 4B). Since the test objects had the same overall brightness values as one another, the chicks could not have used brightness as a low-level cue to distinguish between these objects.

Second, we presented the unfamiliar object from the same viewpoint range as the imprinted object from the input phase. Presenting the unfamiliar object from this viewpoint range increased the V1-level similarity between the unfamiliar object and the imprinting stimulus (Figure 4D). The imprinted object was presented from viewpoint changes of 0°, +30°, and +60° during the test phase. For the 0° viewpoint change, the V1-level within-object image difference was less than the between-object image difference. For the 30° viewpoint change, the V1-level within-object image difference was equivalent to the between-object image difference. And for the 60°

viewpoint change, the V1-level within-object image difference was greater than the between-object image difference.

Third, we tested the chicks on two additional presentation speeds (42 ms and 125 ms).

Results

The results are shown in Figure 3B. Performance was significantly above chance levels for all presentation speeds and viewpoint changes (one-tailed t-tests, all ps < .015), except for the fastest (42 ms) presentation speed (one-tailed t-test, $t(11) = .972$, $p = .176$). A 3×6 repeated-measures ANOVA with Viewpoint Change and Presentation Speed as within-subject factors revealed a significant main effect of Presentation Speed ($F(5, 55) = 3.194$, $p = .013$). The main effect of Viewpoint Change ($F(2, 22) = .143$, $p = .868$) and the interaction ($F(10, 110) = 1.417$, $p = .182$) were not significant. The effect sizes (Cohen's d) for the six presentation speeds were as follows: 42 ms = .28; 125 ms = 1.04; 250 ms = .72; 750 ms = 1.08; 1750 ms = 1.45; 3750 ms = 1.02. The effect sizes for the three viewpoint changes were as follows: 0° azimuth rotation = 1.14; +30° azimuth rotation = 1.09; +60° azimuth rotation = 1.12.

Performance remained stable over the course of the test phase (Figure 3D) with little variation as a function of test trial number (one-way repeated measures ANOVA, $F(6, 66) = 1.171$, $p = .333$). Further, performance on the first presentation of the novel stimuli was marginally significant (one-tailed t-test, $t(11) = 1.67$, $p = .06$, Cohen's $d = .48$). Performance, measured on a minute-by-minute basis, was also stable across the first test trial (one-way repeated measures ANOVA, $F(23, 253) = .621$, $p = .913$). As in Experiment 1, recognition performance was stable over time and cannot be explained by learning taking place across the test phase.

Discussion

These results replicate the general findings from Experiment 1 and show that chicks do not rely solely on overall brightness and V1-level similarity as low-level cues to recognize their imprinted object. These results also confirm that this controlled-rearing method can accurately measure the speed of object recognition in newborn chicks because recognition performance varied as a function of presentation speed. Recognition performance was at chance levels for the fastest presentation speed (42 ms), which shows that this method can prevent chicks from recognizing objects when the successive images are presented quickly enough. Finally, this experiment demonstrates that chicks can recognize objects at presentation speeds of 125 ms.

General discussion

We used an automated controlled-rearing method to measure the speed of object recognition in newborn chicks. The results demonstrated that chicks are capable of both rapid and invariant object recognition. Newborn chicks were able to build a viewpoint-invariant represen-tation of the first object they saw in their life, and recognize that object rapidly (within presentation rates of 125 ms per image). Further, recognition speed was equally fast whether the object was presented from familiar viewpoints or novel viewpoints (30° and 60° azimuth rotations). Thus, newborn chicks can perform the visual processing needed for viewpoint-invariant object recognition tasks within a fraction of a second.[3]

These results replicate previous studies showing that newborn chicks are capable of invariant object recogni-tion (Wood, 2013, 2015; Wood & Wood, 2015), and extend the existing literature by showing that chicks can recognize objects rapidly across novel viewpoints. More generally, this study indicates that two core characteris-tics of object recognition in adult primates – rapid and invariant recognition – are present at the onset of vision in newborn chicks. Prior to the present study, all of the work on rapid object recognition in vertebrates had come from studies using adult animals (reviewed by DiCarlo et al., 2012). The present study extends this literature by showing that rapid object recognition abilities can be present at the onset of vision in avian newborn visual systems. Object recognition abilities appear to be highly conserved across both developmental and evolutionary timescales.

It is important to emphasize that these chicks did acquire experience with extended surfaces during the experiment (e.g. the walls and floor of the chamber and the food/water troughs). In principle, these experiences might have played an important role in the development of object recognition. In previous studies, however, we have shown that these experiences are not sufficient for the development of object recognition. In particular, newborn chicks need visual experience with objects that move slowly and smoothly over time in order to build robust and invariant object representations (Wood, 2016; Wood & Wood, 2016; Wood, Prasad, Goldman & Wood, 2016). In the natural visual world, objects move slowly and smoothly over time. Thus, experience with a natural visual environment appears to calibrate the newborn brain, allowing for the development of high-level object recognition abilities.

These findings do not necessarily imply that newborn chicks build 3D geometric representations of whole objects (Zoccolan et al., 2009). Newborn chicks could build invariant object representations by building invari-ant representations of subfeatures that are smaller than the entire object. These feature detectors might respond to only a portion of the object, or be sensitive to key 2D, rather than 3D, features. In fact, many leading compu-tational models of invariant object recognition in humans and monkeys explicitly rely on such subfeatures (Serre, Oliva & Poggio, 2007; Ullman, Vidal-Naquet & Sali, 2002; Yamins, Hong, Cadieu, Solomon, Seibert et al., 2014). Regardless of the specific nature of these features, our results indicate that newborn chicks are capable of recognizing objects rapidly across novel viewing situations.

In conclusion, the present study introduces a new chronometric method for measuring the speed of object recognition in a newborn animal. This method provides a tool for investigating how object recognition speed changes during development within controlled visual worlds. We anticipate that this automated controlled-rearing method will open up experimental avenues for drawing causal links between the particular visual experiences encountered by newborns and the speed of their mental processes.

Acknowledgements

References

Calabrese, A., & Woolley, S.M.N. (2015). Coding principles of the canonical cortical microcircuit in the avian brain. *Proceedings of the National Academy of Sciences of the United States of America*, **112** (11), 3517–3522.

DiCarlo, J.J., Zoccolan, D., & Rust, N.C. (2012). How does the brain solve visual object recognition? *Neuron*, **73** (3), 415–434.

Dugas-Ford, J., Rowell, J.J., & Ragsdale, C.W. (2012). Cell-type homologies and the origins of the neocortex. *Proceedings of the National Academy of Sciences of the United States of America*, **109** (42), 16974–16979.

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[3] Additional research is needed to determine why the chicks failed to recognize their imprinted object at the fastest (42 ms) presentation speed. Chicks could have failed either because the object images were presented too quickly (42 ms) or because the total stimulus onset asynchrony was too fast (292 ms). Since we used a constant 250-ms inter-stimulus interval across the presentation speeds, our data cannot distinguish between these possibilities. It would be interesting for future studies to further probe chicks' object recognition speed by indepen-dently manipulating the duration of the individual images and duration of the inter-stimulus interval.

Haun, D.B.M., Jordan, F., Vallortigara, G., & Clayton, N.S. (2010). Origins of spatial, temporal and numerical cognition: insights from comparative psychology. *Trends in Cognitive Sciences*, **14**, 552–560.

Intraub, H. (1980). Presentation rate and the representation of briefly glimpsed pictures in memory. *Journal of Experimental Psychology: Human Learning and Memory*, **6** (1), 1–12.

Jarvis, E.D., Gunturkun, O., Bruce, L., Csillag, A., Karten, H., et al. (2005). Avian brains and a new understanding of vertebrate brain evolution. *Nature Reviews Neuroscience*, **6** (2), 151–159.

Karten, H.J. (2013). Neocortical evolution: neuronal circuits arise independently of lamination. *Current Biology*, **23** (1), R12–R15.

Keysers, C., Xiao, D.K., Foldiak, P., & Perrett, D.I. (2001). The speed of sight. *Journal of Cognitive Neuroscience*, **13** (1), 90–101.

Lades, M., Vorbruggen, J.C., Buhmann, J., Lange, J., Vandermalsburg, C., et al. (1993). Distortion invariant object recognition in the dynamic link architecture. *IEEE Transactions on Computers*, **42**, 300–311.

Potter, M.C. (1976). Short-term conceptual memory for pictures. *Journal of Experimental Psychology: Human Learning and Memory*, **2**, 509–522.

Potter, M.C., Wyble, B., Hagmann, C.E., & McCourt, E.S. (2014). Detecting meaning in RSVP at 13 ms per picture. *Attention, Perception, & Psychophysics*, **76** (2), 270–279.

Rousselet, G.A., Fabre-Thorpe, M., & Thorpe, S.J. (2002). Parallel processing in high-level categorization of natural images. *Nature Neuroscience*, **5** (7), 629–630.

Serre, T., Oliva, A., & Poggio, T. (2007). A feedforward architecture accounts for rapid categorization. *Proceedings of the National Academy of Sciences of the United States of America*, **104** (15), 6424–6429.

Thorpe, S., Fize, D., & Marlot, C. (1996). Speed of processing in the human visual system. *Nature*, **381** (6582), 520–522.

Ullman, S., Vidal-Naquet, M., & Sali, E. (2002). Visual features of intermediate complexity and their use in classification. *Nature Neuroscience*, **5** (7), 682–687.

Vallortigara, G. (2012). Core knowledge of object, number, and geometry: a comparative and neural approach. *Cognitive Neuropsychology*, **29** (1–2), 213–236.

Versace, E., & Vallortigara, G. (2015). Origins of knowledge: insights from precocial species. *Frontiers in Behavioral Neuroscience*, **9**, 338. doi:10.3389/fnbeh.2015.00338

Wang, Y., Brzozowska-Prechtl, A., & Karten, H.J. (2010). Laminar and columnar auditory cortex in avian brain. *Proceedings of the National Academy of Sciences of the United States of America*, **107** (28), 12676–12681.

Wood, J.N. (2013). Newborn chickens generate invariant object representations at the onset of visual object experience. *Proceedings of the National Academy of Sciences of the United States of America*, **110** (34), 14000–14005.

Wood, J.N. (2014). Newly hatched chicks solve the visual binding problem. *Psychological Science*, **25** (7), 1475–1481.

Wood, J.N. (2015). Characterizing the information content of a newly hatched chick's first visual object representation. *Developmental Science*, **18** (2), 194–205.

Wood, J.N. (2016). A smoothness constraint on the development of object recognition. *Cognition*, **153**, 140–145.

Wood, J.N., Prasad, A., Goldman, J.G., & Wood, S.M.W. (2016). Enhanced learning of natural temporal sequences in newborn chicks. *Animal Cognition*, **19** (4), 835–845. doi:10.1007/s10071-016-0982-5

Wood, J.N., & Spelke, E.S. (2005). Chronometric studies of numerical cognition in five-month-old infants. *Cognition*, **97** (1), 23–39.

Wood, J.N., & Wood, S.M.W. (2016). The development of newborn object recognition in fast and slow visual worlds. *Proceedings of the Royal Society: Biological Sciences*, **283**, 20160166. doi:10.1098/rspb.2016.0166

Wood, S.M.W., & Wood, J.N. (2015). A chicken model for studying the emergence of invariant object recognition. *Frontiers in Neural Circuits*, **9**, 7. doi:10.3389/fncir.2015.00007

Yamins, D.L.K., Hong, H., Cadieu, C.F., Solomon, E.A., Seibert, D., et al. (2014). Performance-optimized hierarchical models predict neural responses in higher visual cortex. *Proceedings of the National Academy of Sciences of the United States of America*, **111** (23), 8619–8624.

Zoccolan, D., Oertelt, N., DiCarlo, J.J., & Cox, D.D. (2009). A rodent model for the study of invariant visual object recognition. *Proceedings of the National Academy of Sciences of the United States of America*, **106** (21), 8748–8753.

Supporting Information

Additional Supporting Information may be found online in the supporting information tab for this article:

Video S1. Newborn chicks were raised in strictly controlled environments that contained a single virtual object rotating around a single axis.

Video S2. During the test trials, we examined whether newborn chicks could recognize their imprinted object across different presentation speeds and viewpoint changes. This video shows the animations from the 750-ms presentation speed and 30 degree viewpoint change condition.