Spontaneous Preference for Slowly Moving Objects in Visually Naïve Animals

Justin N. Wood[1]

[1]Department of Psychology, University of Southern California

ABSTRACT

To perceive the world successfully, newborns need certain types of visual experiences. The development of object recognition, for example, requires visual experience with slowly moving objects. To date, however, it is unknown whether newborns actively seek out the best visual experiences for developing object recognition. To address this question, I used an automated controlled-rearing method to examine whether visually naïve animals (newborn chicks) seek out slowly moving objects. Despite receiving equal exposure to slowly and to quickly rotating objects, the majority of the chicks developed a preference for slowly rotating objects. This preference was robust, producing large effect sizes across objects, experiments, and successive test days. These results indicate that newborn brains rapidly develop mechanisms for orienting young animals toward optimal visual experiences, thus facilitating the development of object recognition. This study also demonstrates that automation can be a valuable tool for studying the origins and development of visual preferences.

An important goal in the cognitive sciences is to understand how visual preferences shape the development of the mind. Since visual preferences influence where a newborn will look (and thus what information will be extracted from the world), a complete understanding of perceptual and cognitive development requires understanding the nature of early emerging visual preferences. Due to methodological barriers, however, assessments of early visual preferences have so far been based on methods that sample newborns' behavior for short periods of time (e.g., 5–10 min) within a single testing session. As a result, it has not been possible to obtain precise measurements of visual preferences from newborn subjects or examine how visual preferences change over time. To overcome these barriers, I developed an automated controlled-rearing method that can measure newborn subjects' visual preferences continuously (24/7) from the onset of vision. This method makes it possible to measure how visual preferences emerge and change across development, with an unprecedented degree of precision. In the present study, I tested whether newborn animals have an early emerging preference for visual input that is more conducive for building accurate object representations.

Specifically, a growing body of research indicates that visual experience with slowly changing features is essential for the development of vision (e.g., DiCarlo, Zoccolan, & Rust, 2012; Földiák, 1991; Rolls, 2012; Stone, 1996; Wiskott & Sejnowski, 2002). For instance, computational models that extract slowly changing features from the visual environment can account for the self-organization of complex-cell receptive fields (Berkes & Wiskott, 2005), the recognition of whole objects invariant to spatial transformations (Franzius, Wilbert, & Wiskott, 2011), and the self-organization of place cells, grid cells, and head-direction cells (Franzius, Sprekeler, & Wiskott, 2007; Wyss, König, & Verschure, 2006). Moreover, controlled-rearing

experiments provide direct causal evidence that the development of object recognition requires visual experience with slowly moving objects (Wood & Wood, 2016a). When newborn chicks are raised with slowly moving objects, the chicks create invariant object representations that generalize across novel viewpoints and rotation speeds. Conversely, when newborn chicks are raised with quickly moving objects, the chicks create inaccurate object representations that fail to generalize across novel viewing situations. Thus, visual experience with slowly moving objects is critical for the development of object recognition.

If newborns build more accurate object representations when exposed to slowly moving objects, then natural selection might have designed newborn brains to seek out slowly moving objects. This "selective sampling" mechanism would be useful, allowing newborns to avoid wasting precious computational resources on visual material that cannot be transformed into accurate object representations. To test for the existence of such a mechanism, I examined whether newborn chicks, lacking any previous visual experience, show a spontaneous preference to approach slowly moving objects over quickly moving objects.

Newborn chicks are an ideal model system for studying the origins of visual preferences, for several reasons. First, chicks can be raised in strictly controlled environments (e.g., environments containing no real-world objects) from the onset of vision. Thus, with chicks it is possible to study how visual preferences emerge within strictly controlled visual environments. Second, there is evidence that newborn chicks develop visual preferences rapidly (reviewed by Versace & Vallortigara, 2015), and some of these preferences have been linked to specific neural structures (e.g., Di Giorgio et al., 2016; Mayer, Rosa-Salva, Lorenzi, & Vallortigara, 2016). Third, newborn chicks develop high-level object recognition abilities. For instance, newborn chicks can build a view-invariant representation of the first object they see in their life (Wood, 2013, 2015; Wood & Wood, 2015), and can recognize objects rapidly, within a fraction of a second (Wood & Wood, 2016b). Fourth, birds and mammals use homologous neural circuits—with common structural and functional characteristics—to process sensory input (reviewed by Jarvis et al., 2005; Karten, 2013). Accordingly, studies of chicks may reveal general insights into the nature of vertebrate visual development.

EXPERIMENT 1

Methods

Subjects   Twelve Rhode Island Red chicks of unknown sex were tested. The sample size was determined before the experiment was conducted, based on previous automated controlled-rearing experiments with newborn chicks (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 to avoid exposing the chicks to light through their shells. 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   Newborn chicks were raised for five days within specially designed controlled-rearing chambers (66 cm length × 42 cm width × 69 cm height; Figure 1A). To present object stimuli to the chicks, virtual objects were projected on two display walls (19″ LCD monitors with 1,440 × 900 pixel resolution) situated on opposite sides of the chamber. Food (grain) and water were provided within transparent troughs in the ground (66 cm length × 2.5 cm width
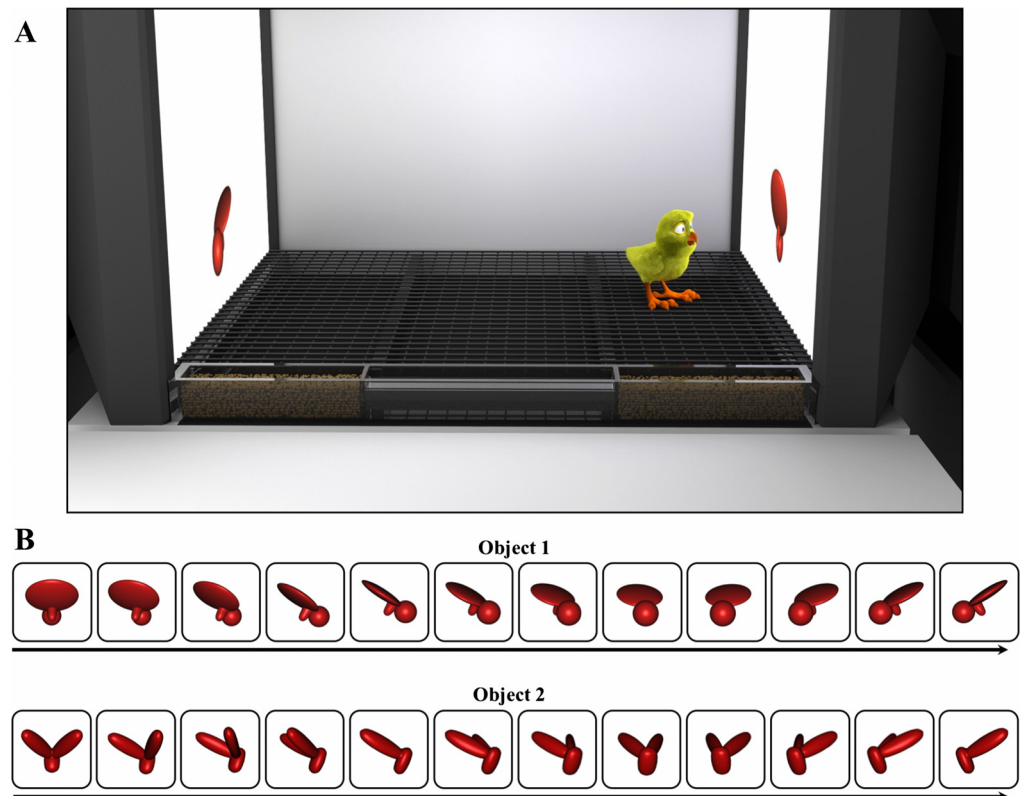
Figure 1. The experimental procedure. (A) Newborn chicks were raised in controlled-rearing chambers that contained a virtual object on each side of the chamber. The objects were identical, but rotated at different speeds. One object rotated once every 15 s (slowly moving object), whereas the other object rotated once per second (quickly moving object). If newborn chicks have a preference for slowly moving objects, then the chicks should spend more time in proximity to the slowly moving object than the quickly moving object. (B) The virtual objects. Half of the chicks were raised with Object 1 and half of the chicks were raised with Object 2.

× 2.7 cm height). The floor of the chamber consisted of black wire mesh supported over a black surface. All animal husbandry was performed in darkness with night vision goggles to avoid exposing the chicks to extraneous visual input.

During each preference trial, the same object was projected on both display walls simultaneously (Figure 1A). On one display wall, the object moved slowly (one rotation every 15 s), whereas on the other display wall, the object moved quickly (one rotation per second). These two rotation speeds were used because newborn chicks build accurate object representations when reared with objects that rotate slowly (one rotation every 15 s) and inaccurate object representations when reared with objects that rotate quickly (one rotation per second) (Wood & Wood, 2016a). By using the same objects and rotation speeds in the present study, it was possible to examine directly whether newborn chicks have a preference for visual stimuli that produces more accurate object representations.

I used rotary motion rather than lateral (picture plane) motion for two additional reasons. First, with rotary motion, it is possible to manipulate an object's motion speed without changing its position in the environment. Second, it is more difficult to make compensatory head and eye movements to adjust for rotary motion compared to lateral motion, allowing for a more direct test of whether newborn chicks have a visual preference for slowly moving objects.

During the experiment, the chicks received equal exposure to the slowly and the quickly moving objects. Thus, the objects were equally familiar to the chicks. If newborn chicks have a spontaneous preference for slowly moving objects, then the chicks should spend more time in proximity to the slowly moving object than the quickly moving object.

To test whether the chicks' visual preferences would generalize across objects, the chicks were raised with one of two objects differing in shape. Half of the chicks were raised with the object shown in the top panel of Figure 1B (see Video S1 in the Supplemental Materials [Wood, 2017]) and half were raised with the object shown in the bottom panel of Figure 1B (see Video S2 in the Supplemental Materials [Wood, 2017]). On average, the objects measured 8 cm (width) $\times$ 7 cm (height) and were suspended 3 cm off the ground. The object rotated in the depth plane around a frontoparallel vertical axis (24 frames/s) and was presented at the middle of the display wall on a uniform white background. The two 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). Videos S1 and S2 in the Supplemental Materials (Wood, 2017) show the animations used in Experiment 1.

Each chick received 120 preference trials during the experiment (one trial per hour over 5 days). Each trial lasted 59 min, followed by a 1-min period of darkness. The slowly and the quickly moving objects switched display walls after each preference trial. The chicks' behavior was tracked continuously using automated image-based tracking software (EthoVision XT, Noldus Information Technology, Leesburg, VA) that calculated the amount of time the chicks spent within zones (22 cm $\times$ 42 cm) next to each object. As a result, I was able to examine (a) whether newborn chicks prefer slowly moving objects, (b) whether this preference emerges at different times in different subjects, and (c) whether this preference changes over time within subjects. In total, 1,440 hr of video footage (5 days $\times$ 24 hr/day $\times$ 12 subjects) were collected for Experiment 1 (120 hr of preference data were collected from each chick). By collecting large amounts of data from each chick, it was possible to achieve low measurement error. For instance, the test-retest reliability of the preference scores across the five days of the experiment was high (Cronbach's alpha = .89).

Results and Discussion

The results are shown in Figure 2. For each trial, I computed the preference score for each chick by dividing the time spent with the slowly moving object by the time spent with both objects. Preference scores above 50% indicate a preference for the slowly moving object and preference scores below 50% indicate a preference for the quickly moving object. The results were analyzed with one-sample t tests compared against chance level (50%). Analyses are included for both the overall group and each individual subject.

Group Performance   For overall group performance, the average preference score was 67.9% (*SEM* = 3%). The chicks spent significantly more time by the slowly moving object than by the quickly moving object (two-tailed one-sample t test: $t(11) = 5.43$, $p < .001$, Cohen's $d = 1.57$). The preference for slowly moving objects occurred both when the chicks were reared with Object 1 [$t(5) = 2.58$, $p = .05$, Cohen's $d = 1.05$] and Object 2 [$t(5) = 7.30$, $p < .001$, Cohen's $d = 2.98$]. As shown in Figure 2C, the chicks spent significantly more time by the slowly moving object during Days 2–5 of the experiment [Day 1: $t(11) = 1.50$, $p = .16$, Cohen's $d = .43$; Day 2: $t(11) = 3.42$, $p = .006$, Cohen's $d = .99$; Day 3: $t(11) = 6.23$, $p < .0001$, Cohen's $d = 1.80$; Day 4: $t(11) = 7.94$, $p < .00001$, Cohen's $d = 2.29$; Day 5:
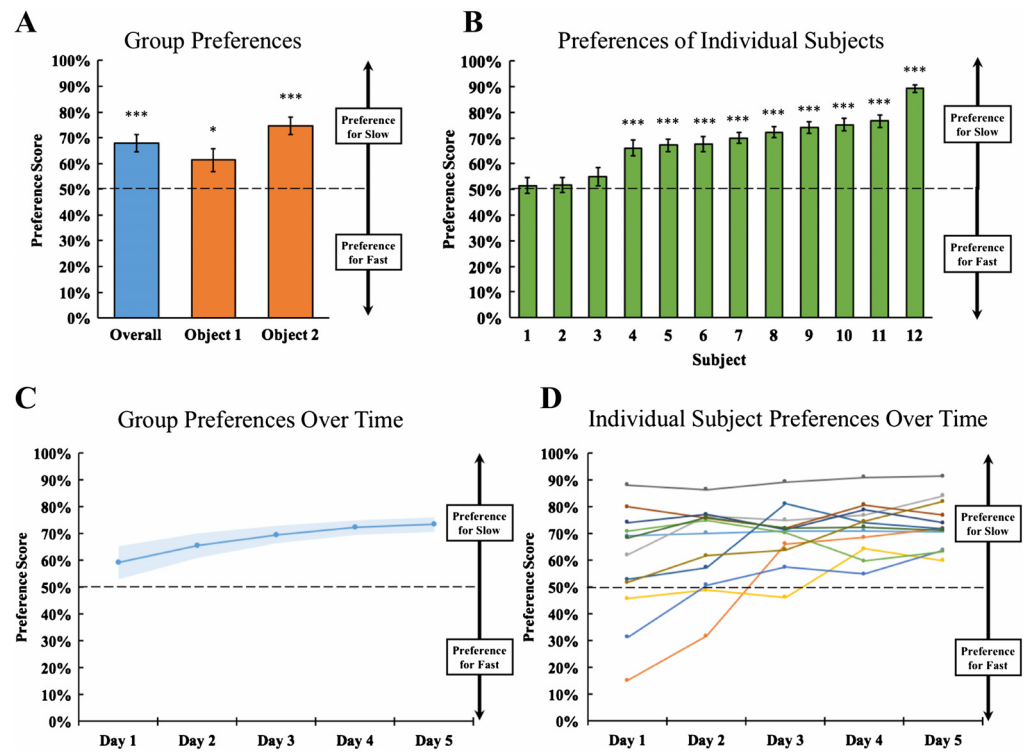
Figure 2.   Experiment 1 results. (A) Group performance. The blue bar shows the preference score for all of the chicks and the orange bars show the preference scores for the chicks reared with each of the two objects. The chicks had a strong preference for the slowly moving object. (B) Individual subject performance. The bars show the preference scores for each chick (ordered by the strength of the preference). The majority of the chicks had a statistically significant preference for the slowly moving object. (C) Change in preference scores across the experiment. Despite receiving equal exposure to the slowly and quickly moving objects, the chicks developed a preference for the slowly moving object. (D) Change in preference scores for each subject. Each line shows the preference scores for one chick across the five days of the experiment. By the end of the experiment, all of the chicks had developed a preference for the slowly moving object. Asterisks denote statistical significance: $*p < .05$; $**p < .01$; $***p < .001$ (two-tailed one-sample t tests). Error bars indicate standard error.

$t(11) = 8.85$, $p < .00001$, Cohen's $d = 2.55$].[1] Notably, these effect sizes are very large (for reference, Cohen considered $d \geq .8$ to be a large effect size; Cohen, 1988).

I also estimated the posterior probability favoring the null hypothesis using the Jeffreys–Zellner–Siow (JZS) Bayes factor (BF_{10}). The Bayes factor is the odds ratio comparing the likelihood of the data fitting under the alternative hypothesis to the likelihood of the data fitting under the null hypothesis. The BF_{10} for the overall preference score was 153.8 (i.e., the alternative hypothesis was 153.8 times more likely than the null hypothesis). Thus, these data provide strong evidence that newborn chicks prefer slowly moving objects.

---

[1] While the group tended to prefer the slowly moving object across the first day (see Figure 3A), the group analysis was not statistically significant for Day 1. The group analysis for Day 1 was also not statistically significant after removing the trials where the chicks were nonresponsive due to rest/sleep [$t(11) = 1.14$, $p = .28$, Cohen's $d = .33$]. Specifically, I removed trials from the analysis whenever two or more successive trials yielded 0%–100% or 100%–0% alternations in preference scores, a pattern that indicates inactivity (see Figure 3B for details).

Individual Subject Performance   Since 120 preference trials were collected from each chick, it was possible to measure each chick's visual preferences with high precision. The preference scores for each chick are shown in Figure 2B. The majority of the chicks (9 out of 12) had a statistically significant preference for slowly moving objects across the experiment (two-tailed t tests: all $p < .001$).

Why did three of the chicks fail to show this preference across the experiment? One possibility is that all chicks eventually develop a preference for slowly moving objects, but that this preference emerges at different times in different subjects. To test this possibility, I charted each chick's preference scores across the five days of the experiment. As illustrated in Figure 2D, there were large differences in the preference scores across chicks. Most of the chicks (8 of the 12) preferred the slowly moving object on Day 1 (two-tailed t tests: 2 subjects, $p < .05$, 2 subjects, $p < .01$, 4 subjects, $p < .001$), but a few of the chicks developed this preference 2–3 days after hatching. Interestingly, two of the chicks started with a strong preference for the quickly moving object, but then lost this preference and developed a new preference for the slowly moving object.
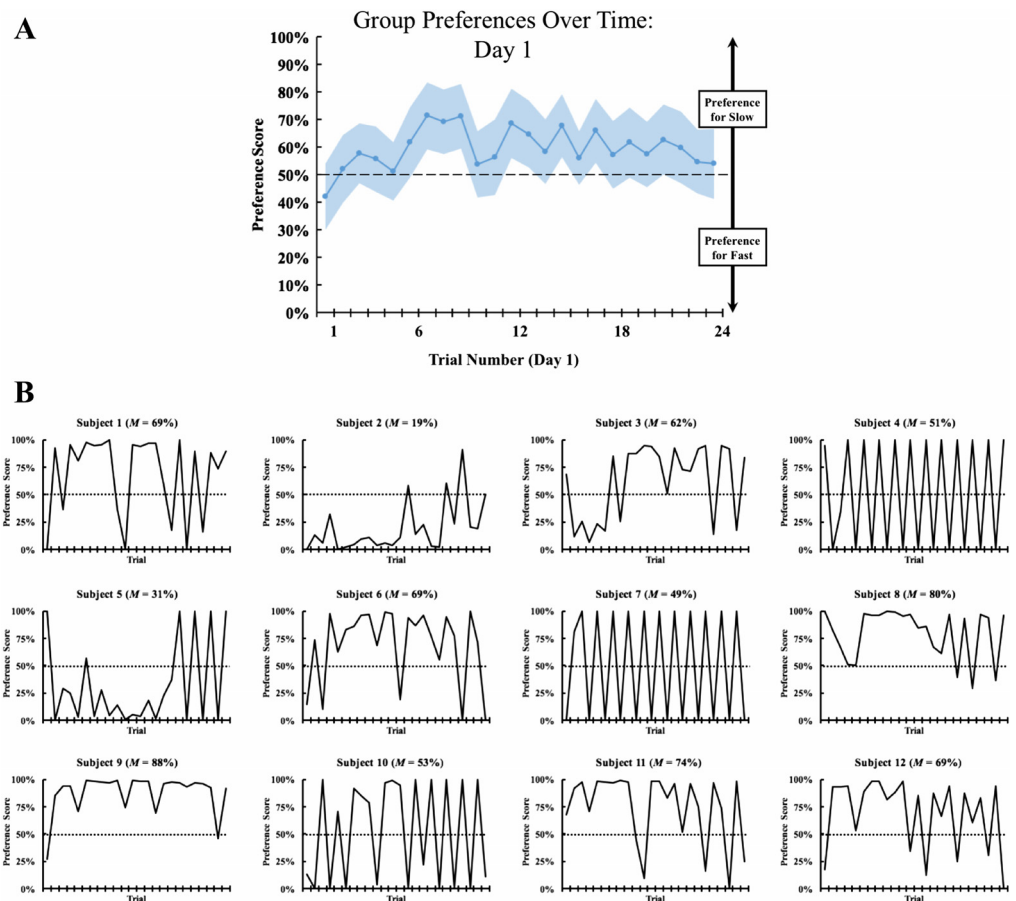
Figure 3. **(A) Change in group preference scores across Day 1 (Experiment 1). (B) Change in preference scores across Day 1 for each subject (Experiment 1).** The graphs show the preference scores across the first 24 trials of the experiment (the chicks received one trial per hour). Large fluctuations in performance across trials (from 0% to 100%) indicate that the chick was stationary/sleeping (i.e., since the objects switched display walls across successive trials, stationary chicks produced large fluctuations in preference scores across trials).

To provide a more fine-grained view of how this visual preference emerged during Day 1, I charted the visual preference scores across the first 24 preference trials of the experiment (Figure 3). Figure 3A shows the group preference scores, while Figure 3B shows each chick's preference scores. While some of the chicks developed a preference for the slowly moving object during their first few hours of exposure to light, other chicks preferred the quickly moving object or showed no clear preference for either object during Day 1. Together, these analyses show that there can be substantial individual differences in the development of this visual preference, even among subjects raised in identical visual environments. Newborn chicks can differ both in the strength of their visual preference and in the timing of when this preference emerges during development.

EXPERIMENT 2

The results from Experiment 1 show that newborn chicks have an early emerging preference for slowly moving objects. However, since the chicks were presented with only two rotation speeds, the nature of this preference remains unclear. In particular, the results are consistent with at least three possibilities. First, newborn chicks might always prefer the slowest moving object in their environment. Second, newborn chicks might prefer the slowest moving object when the speeds of the objects differ by some critical ratio (e.g., when one object moves twice as fast as the other object). Third, newborn chicks might prefer the slowest moving object when one of the objects exceeds a particular speed threshold.

To distinguish between these possibilities, I conducted a second experiment in which the objects rotated at five possible speeds (one rotation every 1.25 s, 2.5 s, 5 s, 10 s, or 20 s). Across the trials, the chicks were presented with all 10 pairwise combinations of these five rotation speeds. If chicks always prefer the slowest moving object in their environment, then they should have a preference for the slowly moving object across all 10 pairwise combinations. Conversely, if chicks prefer slowly moving objects only when the object speeds differ by some critical ratio, then the chicks' preference for the slowly moving object should depend on the ratio between the rotation speeds. Finally, if chicks prefer the slowly moving object only when the quickly moving object exceeds a particular speed threshold, then the chicks should prefer the slowly moving object only when the quickly moving object exceeds a particular rotation speed.

Methods

The methods were identical to those used in Experiment 1, except in the following ways.

First, 11 new subjects were tested. One subject was removed from the analyses because the camera malfunctioned during the experiment. Second, the experiment lasted for 7 days rather than 5 days. This allowed us to collect a larger amount of data from each chick. Third, on each preference trial, the objects could rotate at five possible speeds (one rotation every 1.25 s, 2.5 s, 5 s, 10 s, or 20 s). These successive values differ by a factor of two; thus, with each successive increase in speed, the object rotated twice as fast. The chicks were presented with all 10 pairwise combinations of the five rotation speeds: 1.25 s vs. 2.5 s, 1.25 s vs. 5 s, 1.25 s vs. 10 s, 1.25 s vs. 20 s, 2.5 s vs. 5 s, 2.5 s vs. 10 s, 2.5 s vs. 20 s, 5 s vs. 10 s, 5 s vs. 20 s, and 10 s vs. 20 s.

Each chick received 140 preference trials during the experiment (14 trials for each pairwise combination). Each preference trial lasted 68 min, followed by a 1-min period of

darkness. In total, ~1,848 hr of video footage (7 days × 24 hr/day × 11 subjects) were collected for Experiment 2 (i.e., 168 hr of preference data were collected from each chick).

Results and Discussion

The results are shown in Figure 4. As in Experiment 1, preference scores above 50% indicate a preference for the slowly moving object and preference scores below 50% indicate a preference for the quickly moving object. Across the 10 pairwise combinations, the average preference score was 54.1% (*SEM* = 1%). The chicks spent significantly more time by the slowly moving object than the quickly moving object [two-tailed *t* test: $t(10) = 4.87$, $p < .001$, Cohen's $d = 1.40$]. The preference for slowly moving objects occurred both when the chicks were reared with Object 1 [$t(5) = 3.28$, $p = .02$, Cohen's $d = 1.31$] and Object 2 [$t(4) = 3.45$, $p = .03$, Cohen's $d = 1.54$]. The Bayes factor (BF_{10}) across the 10 pairwise combinations was 58.1 (i.e., the alternative hypothesis that chicks preferred the slowly moving object over the quickly moving object was 58.1 times more likely than the null hypothesis). These data replicate Experiment 1 and provide additional evidence that newborn chicks have a spontaneous preference for slowly moving objects.

To distinguish between the three possibilities described above, I computed the chicks' preference scores for each of the 10 pairwise combinations. As shown in Figure 4, the chicks' preference scores did not vary as a function of the ratio between the rotation speeds. For example, on the trials where there was a 1:4 ratio between the rotation speeds, the chicks preferred the slowly moving object on the 1.25 s vs. 5 s comparison, but not on the 5 s vs. 20 s comparison. The chicks preferred the slowly moving object only when the quickly moving object rotated at the fastest (1.25 s) rotation speed. Thus, these results support the third possibility: newborn chicks prefer slowly moving objects when other objects in the environment exceed a particular speed threshold.
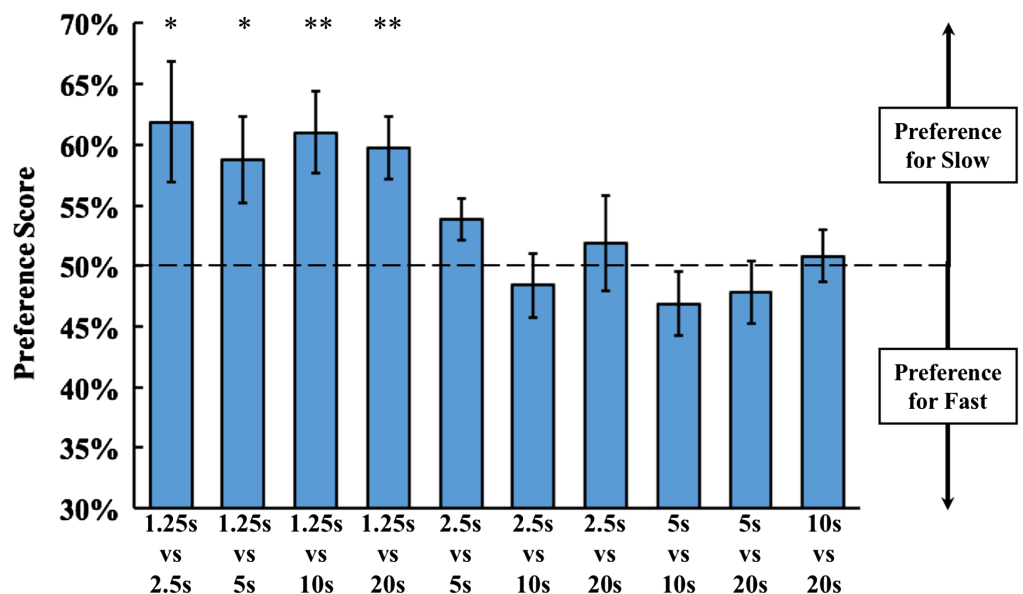
Figure 4. Experiment 2 results. The graph shows the average preference scores for each of the 10 pairwise combinations of the five rotation speeds. Asterisks denote statistical significance: *$p < .05$; **$p < .01$; ***$p < .001$ (two-tailed *t* tests). Error bars indicate standard error.

GENERAL DISCUSSION

Behavioral and computational research indicate that visual experience with slowly changing objects is essential for the development of object recognition (e.g., DiCarlo et al., 2012; Földiák, 1991; Wiskott & Sejnowski, 2002). Newborn chicks, for instance, require experience with slowly moving objects to develop object recognition (Wood & Wood, 2016a). In the present study, I examined whether newborn chicks actively seek out these optimal (slowly moving) object features.

In Experiment 1, newborn chicks were reared with one object that rotated slowly and one object that rotated quickly. The majority of the chicks had a strong preference for the slowly rotating object on their first day of exposure to light. By the end of the experiment, all of the chicks had developed a preference for the slowly rotating object. Experiment 2 replicated this finding and showed that the preference is subject to a threshold effect. Together, these experiments indicate that newborn chicks spontaneously develop a preference for slowly moving objects. This preference was robust, yielding large effect sizes across objects, experiments, and successive test days. Thus, this visual preference for slowly moving objects appears to be a strong driver of behavior. The results also revealed substantial individual differences across subjects, both in terms of the strength of the visual preference and the timing at which this preference emerged during development. To my knowledge, this is the first study revealing significant individual differences in the visual preferences of newborn subjects.

It is important to note that newborn chicks will readily spend time with quickly moving objects when the environment lacks slowly moving objects (Wood & Wood, 2016a), which rules out the possibility that newborn chicks simply avoid quickly moving objects in general. A large literature on avian imprinting also shows that newborn chicks prefer moving objects over stationary objects (reviewed by Horn, 2004). Thus, it is not the case that chicks simply prefer objects that undergo the least amount of visual change. Finally, previous experiments have shown that newborn chicks can recognize these virtual objects when the objects rotate quickly, provided that the objects rotated slowly when being encoded into memory (Wood & Wood, 2016a). Consequently, this preference for slowly moving objects cannot be explained simply as a limitation in the speed of chicks' perceptual abilities.

These findings complement previous studies reporting that newborn chicks have visual preferences for faces (Rosa-Salva, Farroni, Regolin, Vallortigara, & Johnson, 2011), biological motion (Vallortigara, Regolin, & Marconato, 2005), self-propelled motion (Mascalzoni, Regolin, & Vallortigara, 2010), and speed changes (Rosa-Salva, Grassi, Lorenzi, Regolin, & Vallortigara, 2016), and extend this literature by demonstrating that newborn chicks have a visual preference for slowly moving objects. This is an important addition to the literature because experience with slowly moving objects is required for the development of object recognition (Wood & Wood, 2016a). This visual preference may drive the development of object recognition by motivating newborn animals to seek out the best visual inputs for constructing accurate mental models of objects. It would be interesting for future studies to measure newborn chicks' visual preferences for faces, biological motion, and self-propelled motion with the automated controlled-rearing method described here, thereby allowing for a direct comparison of the strength of these different early emerging visual preferences.

Additional research is needed to characterize the development of this visual preference more precisely. For example, chicks might develop a preference for slowly moving objects from their experiences with a slowly changing environment or from their experiences with their own movements. Future studies are also needed to characterize the nature of this visual preference

more formally. For instance, there is evidence that human infants prefer visual experiences that are optimal in their complexity (e.g., Kidd, Piantadosi, & Aslin, 2012; Oudeyer & Smith, 2016). Likewise, it is possible that quickly moving objects are more complex (difficult to process) than slowly moving objects, and that newborn chicks prefer objects that are optimal in their complexity.[2]

In what ways do these results illuminate visual development in humans? On the neural level, there is growing evidence that birds and mammals use homologous neural circuits to process sensory input (reviewed by Jarvis et al., 2005; 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 (Reiner, Yamamoto, & Karten, 2005), the connectivity pattern of the input and output neurons (Wang, Brzozowska-Prechtl, & Karten, 2010), gene expression (Dugas-Ford, Rowell, & Ragsdale, 2012), and function (Calabrese & Woolley, 2015). If newborn chicks and human infants use homologous neural circuits to process sensory input—as these studies suggest—then chicks and infants might share common visual preferences.

On the behavioral level, these results accord with a large body of work in developmental psychology showing that human infants prefer slow speech over fast speech (e.g., Cooper & Aslin, 1990; Fernald et al., 1989). When talking to infants, adults typically use a unique speech register known as infant-directed speech (IDS), and a slow speaking rate is one of the most distinctive characteristics of IDS. There is also evidence that infants learn words more effectively when adults use slower speaking rates (Song, Demuth, & Morgan, 2010), akin to how newborn chicks build more accurate object representations when raised with slowly moving objects (Wood & Wood, 2016a). Thus, human infants and newborn chicks both prefer slowly changing sensory input and show enhanced learning from slowly changing sensory input.

Finally, an important contribution of this study is to introduce an automated controlled-rearing method for studying visual preferences in newborn subjects. Using automation, it is possible to sample behavior continuously (24/7) and chart how visual preferences change across the first days of life. Automation also allows large amounts of data to be collected from each subject, which reduces measurement error and increases the power of the design. Given growing evidence that published findings are more likely to be false when measurement error is high (e.g., Ioannidis, 2005; Loken & Gelman, 2017), automation may be a valuable tool for combating the replication crisis in psychology.

In summary, the present study provides evidence for a spontaneous visual preference for slowly moving objects in visually naïve newborn chicks. This study also introduces a powerful automated controlled-rearing method for probing the origins and development of visual preferences in a newborn model system.

---

[2] Another possibility is that the fast rotation speed impaired the chicks' ability to perceive continuous motion. Since both objects were presented at 24 frames per second, the quickly moving object rotated a greater distance across successive frames than the slowly moving object. Thus, the slowly moving objects were more *temporally smooth* than the quickly moving objects, a factor that influences the development of object recognition (Wood, 2016). It would be interesting for future studies to systematically manipulate both the speed and temporal smoothness of objects to examine how these factors influence newborn chicks' early emerging visual preferences.

AUTHOR CONTRIBUTIONS

JNW designed the research, performed the research, analyzed the data, and wrote the article.

REFERENCES

Berkes, P., & Wiskott, L. (2005). Slow feature analysis yields a rich repertoire of complex cell properties. *Journal of Vision*, *5*, 579–602.

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*, *112*, 3517–3522.

Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Lawrence Erlbaum.

Cooper, R. P., & Aslin, R. N. (1990). Preference for infant-directed speech in the first month after birth. *Child Development*, *61*, 1584–1595.

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

Di Giorgio, E., Loveland, J. L., Mayer, U., Rosa-Salva, O., Versace, E., & Vallortigara, G. (2016). Filial responses as predisposed and learned preferences: Early attachment in chicks and babies. *Behavioural Brain Research*, *325*(Pt. B), 90–104. doi:10.1016/j.bbr.2016.09.018

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*, *109*, 16974–16979.

Fernald, A., Taeschner, T., Dunn, J., Papousek, M., de Boysson-Bardies, B., & Fukui, I. (1989). A cross-language study of prosodic modifications in mothers' and fathers' speech to preverbal infants. *Journal of Child Language*, *16*, 477–501.

Földiák, P. (1991). Learning invariance from transformation sequences. *Neural Computation*, *3*, 194–200.

Franzius, M., Sprekeler, H., & Wiskott, L. (2007). Slowness and sparseness lead to place, head-direction, and spatial-view cells. *PLoS Computational Biology*, *3*(8), e166.

Franzius, M., Wilbert, N., & Wiskott, L. (2011). Invariant object recognition and pose estimation with slow feature analysis. *Neural Computation*, *23*, 2289–2323.

Horn, G. (2004). Pathways of the past: The imprint of memory. *Nature Reviews Neuroscience*, *5*, 108–120.

Ioannidis, J. P. A. (2005). Why most published research findings are false. *PLoS Med*, *2*(8), e124. doi:10.1371/journal.pmed.0020124

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

Karten, H. J. (2013). Neocortical evolution: Neuronal circuits arise independently of lamination. *Current Biology*, *23*, R12–15.

Kidd, C., Piantadosi, S. T., & Aslin, R. N. (2012). The Goldilocks effect: Human infants allocate attention to visual sequences that are neither too simple nor too complex. *PLoS ONE*, *7*(5), e36399.

Loken, E., & Gelman, A. (2017). Measurement error and the replication crisis. *Science*, *355*, 584–585.

Mascalzoni, E., Regolin, L., & Vallortigara, G. (2010). Innate sensitivity for self-propelled causal agency in newly hatched chicks. *Proceedings of the National Academy of Sciences*, *107*, 4483–4485.

Mayer, U., Rosa-Salva, O., Lorenzi, E., & Vallortigara, G. (2016). Social predisposition dependent neuronal activity in the intermediate medial mesopallium of domestic chicks (*Gallus gallus domesticus*). *Behavioral Brain Research*, *310*, 93–102.

Oudeyer, P.-Y., & Smith, L. B. (2016). How evolution may work through curiosity-driven developmental process. *Topics in Cognitive Science*, *8*, 492–502.

Reiner, A., Yamamoto, K., & Karten, H. J. (2005). Organization and evolution of the avian forebrain. *The Anatomical Record Part A: Discoveries in Molecular, Cellular, and Evolutionary Biology*, *287A*, 1080–1102.

Rolls, E. T. (2012). Invariant visual object and face recognition: Neural and computational bases, and a model, VisNet. *Frontiers in Computational Neuroscience*, *6*, 1–70.

Rosa-Salva, O., Farroni, T., Regolin, L., Vallortigara, G., & Johnson, M. H. (2011). The evolution of social orienting: Evidence from chicks (Gallus gallus) and human newborns. *PLoS ONE*, *6*(4), e18802.

Rosa-Salva, O., Grassi, M., Lorenzi, E., Regolin, L., & Vallortigara, G. (2016). Spontaneous preference for visual cues of animacy in naïve domestic chicks: The case of speed changes. *Cognition*, *157*, 49–60.

Song, J. Y., Demuth, K., & Morgan, J. (2010). Effects of the acoustic properties of infant-directed speech on infant word recognition. *Journal of the Acoustical Society of America*, *128*, 389–400.

Stone, J. V. (1996). Learning perceptually salient visual parameters using spatiotemporal smoothness constraints. *Neural Computation*, *8*, 1463–1492.

Vallortigara, G., Regolin, L., & Marconato, F. (2005). Visually inexperienced chicks exhibit spontaneous preference for biological motion patterns. *PLoS Biology*, *3*(7), e208.

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*, *107*, 12676–12681.

Wiskott, L., & Sejnowski, T. J. (2002). Slow feature analysis: Unsupervised learning of invariances. *Neural Computation*, *14*, 715–770.

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

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

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

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

Wood, J. N. (2017). Supplementary videos: The controlled-rearing chambers with Objects 1 and 2. Supplemental material for "Spontaneous preference for slowly moving objects in visually naive animals." *Open Mind: Discoveries in Cognitive Science*, *1*(2), 111–122. doi:10.1162/opmi_a_00012

Wood, J. N., & Wood, S. M. W. (2016a). The development of newborn object recognition in fast and slow visual worlds. *Proceedings of the Royal Society B: Biological Sciences*, *283*(1829). doi:10.1098/rspb.2016.0166

Wood, J. N., & Wood, S. M. W. (2016b). Measuring the speed of newborn object recognition in controlled visual worlds. *Developmental Science*, *20*, e12470. doi:10.1111/desc.12470

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), 1–12. doi:10.3389/fncir.2015.00007

Wyss, R., König, P., & Verschure, P. (2006). A model of the ventral visual system based on temporal stability and local memory. *PLoS Biology*, *4*(5), e120.

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*, *106*, 8748–8753.