



UNIVERSITÀ
DEGLI STUDI
DI PADOVA



ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

UNIVERSITÀ DEGLI STUDI DI PADOVA

Department of Biomedical Science

*Interuniversity Bachelor's degree programme
in Biology of Human and Environmental Health*

Final dissertation

**PRIME AND NON-PRIME NUMBERS DISCRIMINATION
IN NEWBORN CHICKS (*Gallus gallus*)**

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Abstract

Previous studies on both human infants and baby domestic chickens showed that, after exposure to sets of even numerosities, subjects discriminate and spontaneously prefer prime (7 or 11) over non-prime (9) novel sets. This discrimination is considered to be based on a perceptual property unique to prime numbers, namely the impossibility to disassemble a prime set into same-sized subsets, (e.g. $9 = 3+3+3$, however $7 = 3+4$ or $2+2+3$, etc). However, the direction of the preference toward prime sets remains unclear. Either the experimental task favoured exploration of the set perceived as more novel (the prime one) from the habituation (all even numerosities), or there is a sheer innate preference for prime numerosities. Here, we address this issue, replicating prime vs non-prime spontaneous preference test previously performed on chicks, without the initial habituation phase to even sets. One-day old *Gallus gallus* chicks were placed in an artificial arena and habituated to a white square on a black monitor (Exp.1) or with a cross constantly changing position in the white square, to attract chicks' attention toward the area where the stimuli will be projected at test (Exp.2). At test, chicks were presented with two sets of novel elements, a prime and a non-prime numerosity (7 vs 9 or 9 vs 11), and the time spent in proximity of each stimulus was analyzed as a proxy of their preference. The results could contribute to the ongoing debate on whether prime numbers possess distinctive properties that are relevant to biological systems.

1. Introduction

A longstanding question is whether mathematical concepts are invented by humans or discovered as properties of the natural world. In fact, many instances of mathematical laws can be observed in nature. Prime numbers provide an interesting example: although formally defined within mathematics, patterns related to prime numbers have been observed in both biological systems and perceptual processes. For instance, there is evidence in biology and entomology that North American Cicadas follow periodic lifecycles emerging from the ground, where they remained as nymphs, exclusively every 13 to 17 years^{[1][2]}. The fact that the duration of their life cycle is a prime number may not be coincidental, as it offers several advantages, from preventing species hybridization to representing a survival strategy to avoid overlapping predator cycles. Yet, the mechanism behind this and other mathematically peculiar occurrences embodied in biological settings remains an unsolved enigma.

From a perceptual point of view, prime numbers present unique properties related to the impossibility of creating all same-sized subsets out of a prime-numbered array of elements^[3]. While both even and odd composite numbers can always be decomposed into subsets of equal size (e.g. $9 = 3+3+3$ and $6 = 2+2+2$ or $3+3$), prime numbers can only be divided asymmetrically, leaving at least one subgroup with a different number of elements (e.g. $7 = 2+2+3$ and $11 = 4+4+3$) (Figure 1). Symmetrical grouping is a spontaneous perceptual strategy deeply rooted in Gestalt principles of visual perception. Prime number discrimination connects directly to these psychological laws: the principle of symmetry facilitates the perception of a unified whole; the principle of similarity supports the grouping of elements similar to each other; and the law of Prägnanz favors the processing of simple and regular configurations over complex ones. Visual grouping of prime sets violates these principles, possibly creating a perceptual difference of prime compared to non-prime arrays.

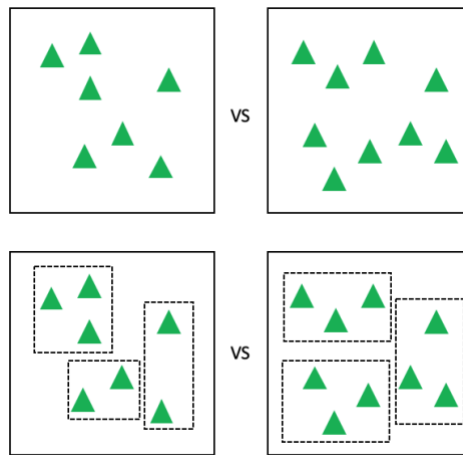


Figure 1

Example of visual perceptual strategy applied in the elaboration of a prime (i.e. 7) vs a non-prime (i.e. 9) sets of elements highlighting respectively asymmetrical and symmetrical groupings

Studies from clinical and experimental psychology on individuals with different levels of mathematical skills suggested the existence of an innate grouping ability involving perceptual asymmetry processing rather than mathematical concepts. When presented sets of dots grouped in subgroups to enumerate them, subjects' performance decreased when the set observed was a prime number quantity: the correspondent delay in response was interpreted as a requirement for longer processing times, given that asymmetrical visual information is perceived as more complex and difficult to process. This pattern was explained as the need to rely on both multiplicative and additive strategies, rather than only one of the two like in the processing of non-prime numbers. [4][5]

The first study to directly investigate the existence of perceptual mechanisms for discriminating prime vs non-prime sets of elements was carried out on newborn chicks. In literature, newborn chicks (*Gallus gallus*) have already demonstrated to possess the ability to process numerical information, discriminating between numerosities and solving basic arithmetic operations^{[9][10][11][12]}. Furthermore, being a precocial species, meaning they are fully developed at hatching and can autonomously navigate and interact with the environment around them, chicks represent the optimal animal model for these studies focused on predisposition at birth.

In a series of experiments, newborn chicks underwent a one-hour habituation to even numerosities (i.e. 4, 6, 8, 10) immediately after hatching. Each single subject was left free to explore a triangular plastic arena where an even quantity of stimuli was displayed on one of the sides. Afterwards, during testing, in the same arena used for habituation, subjects were presented with two novel odd numerosities (i.e. 5vs9 or 7vs9 or 9vs11), one on each side of the monitor, parted by a plastic vertical partition. Importantly, one set was a prime number (non-composite and only divisible in asymmetric subgroups, i.e. 5, 7, 11) while the other was a non-prime number (divisible in symmetrical subgroups, i.e. 9). Their preference was assessed as time spent in proximity of the visual stimuli during a total span of six minutes. Results of the study revealed that chicks spent overall longer time inspecting the set of prime number elements, irrespective to its magnitude (i.e. whether it was the smaller or the larger of the comparison), supporting the hypothesis of chicks relying on a perceptual grouping that allowed them to discriminate prime from non-prime sets. ^{[13][14][15][16]}

These results were also replicated in our species with tests on preverbal 8-month-old infants^[6]: after habituation to sets of even numerosities, subjects were to express their preference between sets of non-prime odd numerosities (can be divided in equal subgroups) or prime-numbers (cannot be divided in equal subgroups). A preference toward the prime sets resulted in a higher number of orientations; this preference could not be explained by numerical magnitude as subjects preferred both the smaller and larger prime number, nor due to numerical ratio as it was too high to allow discrimination via numerical processing^{[7][8]}. This result suggests the involvement of a perceptual grouping mechanism similar to other organizational principles pertaining to newborns.

The present research thesis closely follows the methodology applied in previous research conducted on baby chicks, the only difference being that we removed the initial phase of habituation. This would allow to define whether the preference for prime numbers observed in prior studies is driven by an innate inclination toward prime numbers, or are rather the response to novelty resulting from habituation to even numbers. Exposure is a critical phase to guide newborn chicks toward the artificial screen: without prior exposure to the LED panels employed during testing, subjects might freeze, show decreased attention span or actively avoid the novel unfamiliar object. Substituting habituation to even numbers with a blank screen habituation is crucial to determine whether the outcome is the effect of novelty in response to prior exposure to even numbers or just an intrinsic tendency toward

prime numbers. In prior research^{[14][16]}, chicks were exposed to even numbers which, being composite numbers, are always perceived as symmetrical subsets, meaning subjects already experienced this type of visual configuration during habituation. During testing, odd composite numbers, still decomposable into symmetrical subgroups (i.e. $9 = 3+3+3$), allowed chicks to rely on the same familiar symmetrical visual scheme observed during habituation. Prime numbers instead can only be perceived as asymmetrical subgroups (i.e. $7 = 2+2+3$ or $11 = 3+4+4$), representing therefore an unfamiliar visual input. An inclination toward novel stimuli has already been documented in several studies on newborn chicks, so results obtained in prime-number discrimination studies to date might also reflect the response to novelty^{[17][18]}. A blank screen habituation allows to precisely discriminate a response to novelty from a spontaneous numerical preference. Since chicks were exposed to neither prime nor non-prime numbers, both the stimuli presented during test were equally perceived as novel. If the research resulted in no clear choice toward prime numbers, this would most likely exclude the hypothesis of an innate preference, in favor of the option of a response to novelty. Conversely, if the same procedure resulted in chicks showing a defined preference for prime numbers, this would support the hypothesis of an innate biological predisposition and prime numbers discrimination would need to be explored as a possible phylogenetically ancient core knowledge system present at birth and shared across species. Confirming an inborn preference for prime numbers in *Gallus gallus* would provide a decisive insight into how these mathematical mechanisms play a fundamental role in animal cognition.

2. Methodology

2.1 Subjects

Fertilised domestic chicken (*Gallus gallus*) eggs were provided by a local hatchery (Incubatoio La Pellegrina, San Pietro in Gu, Padova, IT). Eggs were incubated in darkness at controlled temperature (37.5°C) and humidity (55–66%) in the laboratory. Upon hatching, subjects were weighed and sexed by the wing through visual inspection of the primary and covert feathers' length. Both male and female chicks were used in this study as, based on previous studies, there were not relevant sex-related behavioral differences to be expected. All chicks were tested within 24h after hatching. At the

end of the experimental procedures, animals were donated to local farmers. The experiments complied with all applicable national and European laws concerning the use of animals in research and were approved by the Italian National Ministry of Health (N.I.H.). All procedures employed in the experiments included in this study were approved by the Italian Ministry of Health (permit number: 196/2017-PR granted on 24/02/2017).

2.1.1. Rearing conditions.

After habituation, the procedure involved: weighing, sexing and naming chicks. Each chick was individually housed in a standard metal cage (28x32x40 cm) with water for one hour before moving to test. Once the experiment was concluded, chicks were housed together in social groups of two or three individuals. Water and food were available *ad libitum*. Additionally, chicks were fed *Tenebrio molitor* larvae as part of a supplementary diet. A 36W lamp was placed 45 cm above the cage floor and provided light according to a temporized light-dark cycle (light from 7am to 7 pm, followed by dark-light alternated phases of 2/3h each).

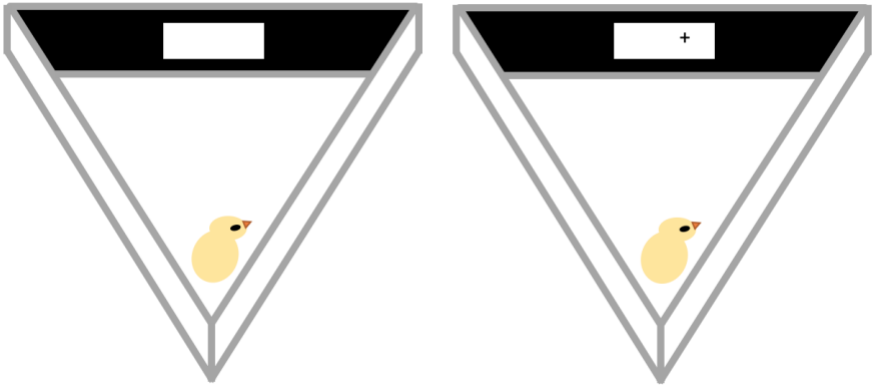
2.2 Procedure

2.2.1 Habituation

Chicks were divided in two groups, the first formed by 40 individuals, the second by 20 individuals. In both cases chicks were kept in the dark within the incubator to avoid any visual experience prior to habituation. Post-hatching, directly from the incubator, chicks were placed, once at the time, in a triangular arena (93 cm x 62 cm x 30 cm) where the side of the triangle opposite to the starting vertex, where the chick was positioned, consisted in a computer screen (Samsung FHD, 24", 60 Hz refresh rate). Chicks were left free to move in the arena for 1h. During this time, for the first experiment a white area (336px) was presented on the monitor, while for the second experiment to the same white screen was added a small attention-getter stimulus: a cross of the same dimension (36xp) of the stimuli

later on used in the test (Figure 2A), that randomly changed position within the blank space every 10sec (Figure 2B).

A



B

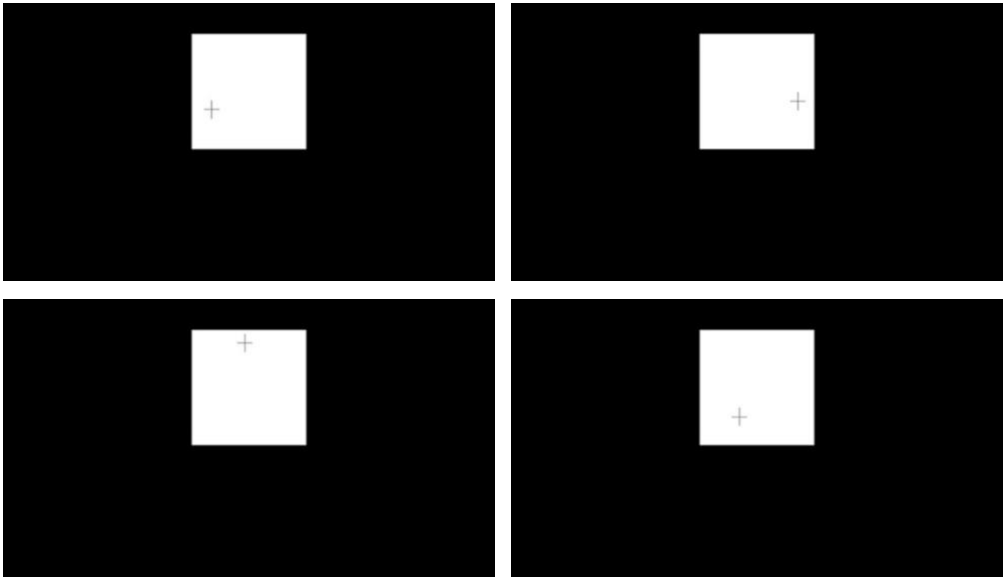


Figure 2

- (A) During habituation procedure, chicks were left free to explore the triangular arena, later used also for the test, for a period of 60 minutes. In this hour, for the first experiment, the computer screen on one side of the arena presented a blank white square while for the second experiment, to the blank screen was added a moving attention-getter cross.
- (B) During the phase of habituation, for the second experiment, to the same white square presented on the screen during the first experiment was added a small cross randomly and periodically changing position inside the blank space, to keep the chicks engaged with the environment.

2.2.2. Test.

At test, chicks were individually placed in one vertex of a triangular arena (93 cm x 62 cm x 30 cm), the same used for habituation. Opposite to the vertex, the computer screen presented two different stimuli, divided by a vertical partition (5x30cm), each consisting of numerical groupings containing the same number of elements but changing shape, color and position within the white square. (Figure 3A)

The two stimuli presented at the same time always shared shape and color but had different numerosities. Each pair of stimuli changed shape and color every 10s. During the first experiment, subjects were given two different numerical comparisons (7vs9, 9vs11), one of the two was randomly assigned to each individual chick. The second experiment instead presented a single comparison (9vs11). The position of the larger group was counterbalanced between subjects. For the test, once the camera (Canon-Legria HF-R606) was turned on, the chick was neutrally positioned in the vertex of the arena opposite to the screen, lights were turned off and the subject was allowed to freely explore the stimuli for 6 minutes. (Figure 3B)

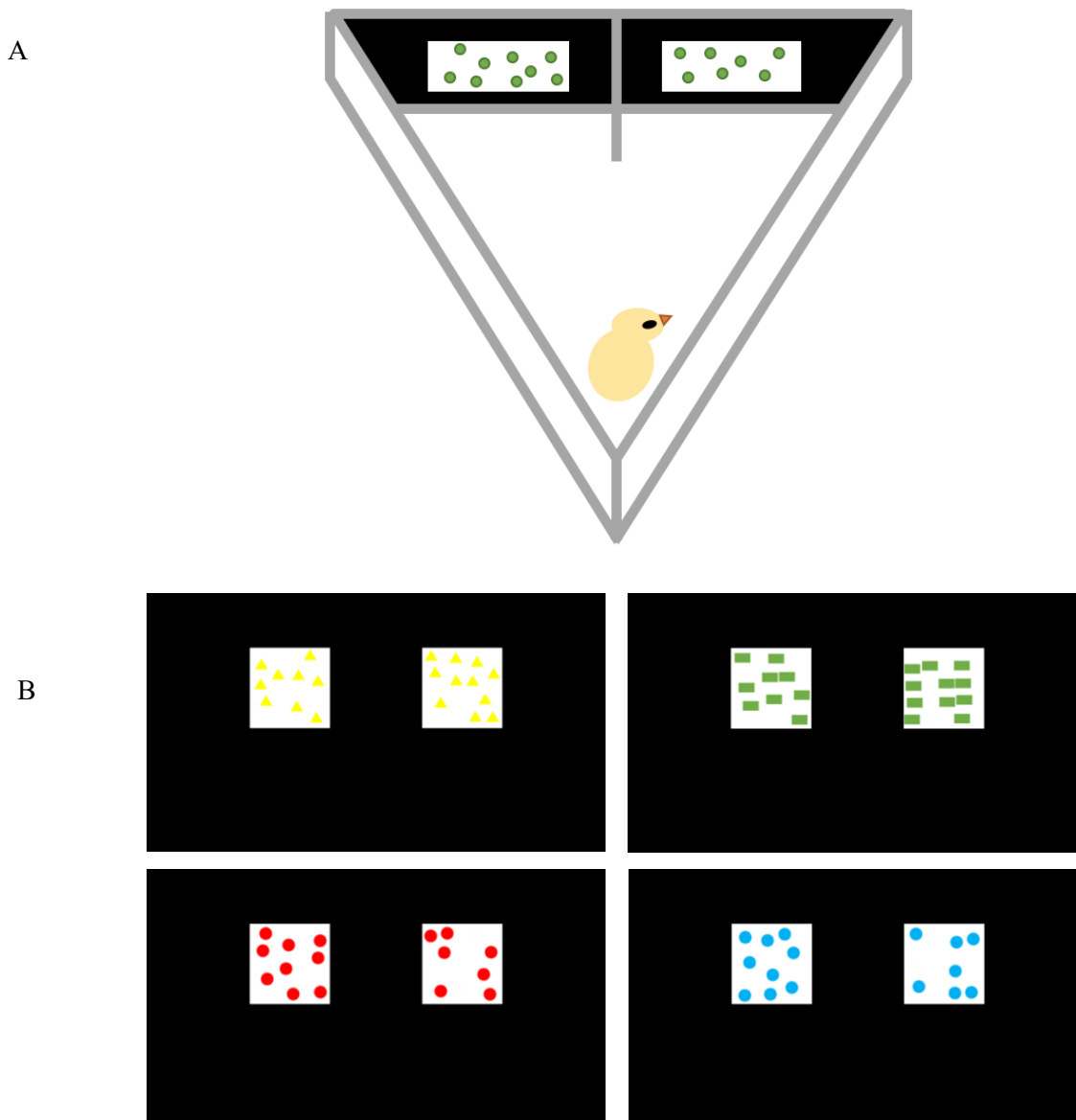


Figure 3

- (A) During test, the screen representing one side of the arena was divided by an opaque vertical partition into two identical areas. In each of them was displayed the same white square showed during habituation, with the addition of different sets of visual stimuli.
- (B) Visual cues differed for color (red, yellow, green, blue), shape (circles, squares, triangles) and numerosity (7,9,11). The same side of the screen maintained constant the number of stimuli while color and shape changed simultaneously and correspondingly in both sides.

2.2.3. Data analysis

Testing procedures are video recorded by a camera placed about 30 cm above the arena. The videos are downloaded daily after experimental procedures and analyzed using BORIS software^[19].

The program was set to measure the time each chick spent in proximity to each of the two stimuli present in the arena, starting to consider interest for one of the two from when the subject crossed with half of the body the vertical partition dividing the two numerical sets. Proximity, likewise in analogous studies ^{[13][14]}, was used as a preference index for the numerosity presented in the relative area, as once close to one of the numerosities, the other couldn't be seen due to the vertical partition dividing the two stimuli. (Figure 4)

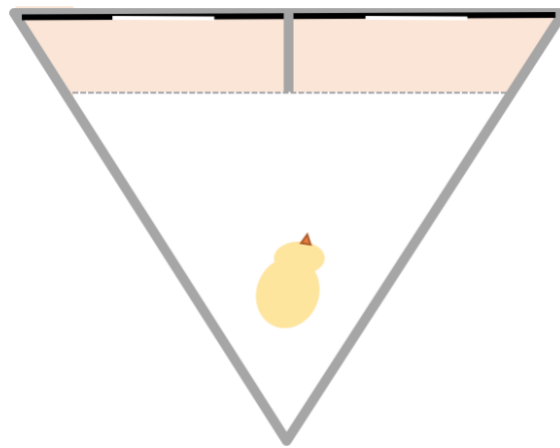


Figure 4

Proximity to the numerosity started to be considered a preference from the moment the subject crossed the abstract horizontal line perpendicular to the vertical partition (dashed line in the picture), entering the area highlighted in pink with at least one leg and the head.

The videos were scored by independent unbiased scorers. Data were analyzed using R software^[20], through a Linear Mixed-Effects Model (LMM) where both stimuli (i.e. 7, 9, 11) and experimental conditions (7vs9, 9vs7, 9vs11, 11vs9) were entered as fixed factors, while subjects were included as random effect.

3. Results

3.1 Experiment 1

During the first experiment, following habituation to a blank screen, chicks were presented with two numerical comparisons (7vs9 and 9vs11). We analyzed the total time spent near each stimulus during the full 6-minutes testing procedure, using proximity as a proxy for preference. The analysis revealed a significant main effect on the stimulus ($X^2 = 10.33$, $p = 0.006$) and of the experimental condition ($X^2 = 5.22$, $p = 0.022$). Post-hoc analyses indicated a preference for the prime number. Specifically, chicks spent significantly more time near the prime number 7 compared to the composite number 9 (estimate = 78.7, SE = 25.0, $t = 3.15$, $p = 0.003$). No statistically relevant difference emerged in the comparison involving larger magnitude numbers (9vs11: estimate = 16.0, SE = 24.5, $t = 0.655$, $p = 0.516$) (Figure 5).

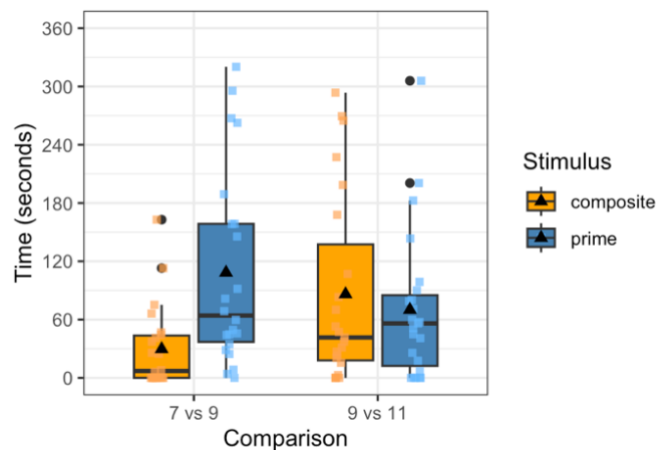


Figure 5

First experiment: Total time spent in proximity to each stimulus during the full 6-minute testing phase following blank habituation. The y-axis represents the time spent in proximity to each stimulus in seconds; the x-axis indicates the numerical comparisons. Blue boxes denote time spent close to prime numerosities (7 or 11); orange boxes denote time spent close to the composite numerosity (9). Black dots represent outliers; black triangles represent the mean.

The same analysis was conducted on a shorter temporal window analyzing preference solely during the first minute following the chick's first choice. These results closely mirror the 6-minute data: stimulus retained a statistically relevant effect ($X^2 = 14.61$ $p = 0.0007$), while experimental condition ($X^2 = 0.67$ $p = 0.412$) did not reach significance.

Gathering stimuli as prime (7 and 11) and composite (9) for further analysis, a robust overall preference is manifested for prime over composite stimuli (estimate = -16.3, SE = 4.65, $t = -3.506$, $p = 0.001$)

Regarding the specific experimental conditions during the first minute, 7vs9 (estimate = 23.42, SE = 6.63, $t = 3.53$, $p = 0.001$) remained the only condition demonstrating a significant preference for the prime number. The larger magnitude pairing 9vs11 (estimate = -9.48, SE = 6.49, $t = -1.461$, $p = 0.151$) yielded non-significant results (Figure 6).

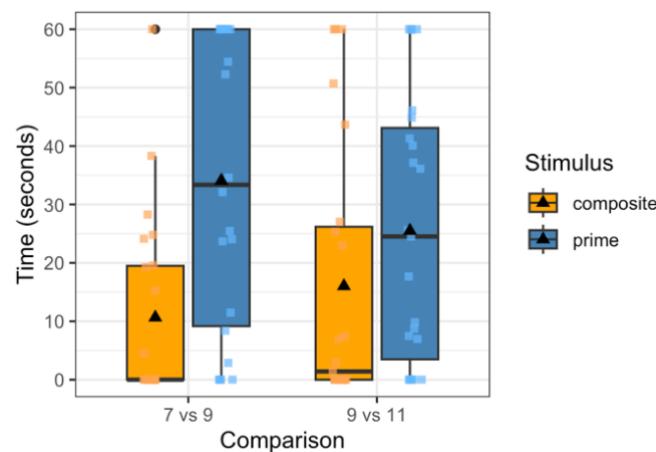


Figure 6

First experiment: Time spent in proximity to each stimulus during the first minute starting after the subject's first choice, following blank habituation. The y-axis represents the time spent in proximity to each stimulus in seconds; the x-axis indicates the numerical comparisons. Blue boxes denote time spent close to prime numerosities (7 or 11); orange boxes denote time spent close to the composite numerosity (9). Black dots represent outliers; black triangles represent the mean.

3.2 Experiment 2

During the second experiment, following habituation to a white screen with a small cross regularly changing position within it, chicks were presented a single numerical comparisons (9vs11). From the analysis of the time spent in proximity of each stimulus during the full 6-minute testing process, stimuli failed to provide a relevant effect ($X^2 = 0.17$ $p = 0.681$). Furthermore, no statistical relevance was provided by results in the comparison (estimate = 10.1, SE = 24.6, $t = -0.41$, $p = 0.685$) (Figure 7).

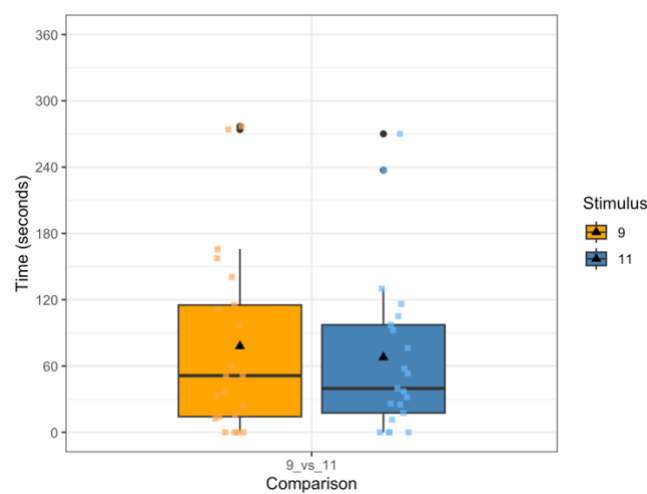


Figure 7

Second experiment: Total time spent in proximity to each stimulus during the full 6-minute testing phase following habituation to white screen with a moving cross. The y-axis represents the time spent in proximity to each stimulus in seconds; the x-axis indicates the numerical comparison. Blue box denote time spent close to the prime numerosity (11); orange box denote time spent close to the composite numerosity (9). Black dots represent outliers; black triangles represent the mean.

Results from the same analysis conducted on a one-minute window starting from the chick's first choice reflect results from the total testing time analysis: stimuli were revealed to be non-relevant ($X^2 = 0.17$ $p = 0.678$). In the same way, preference between prime and composite stimuli wasn't statistically relevant: estimate = -1.23, SE = 2.96, $t = -0.42$, $p = 0.682$ (Figure 8).

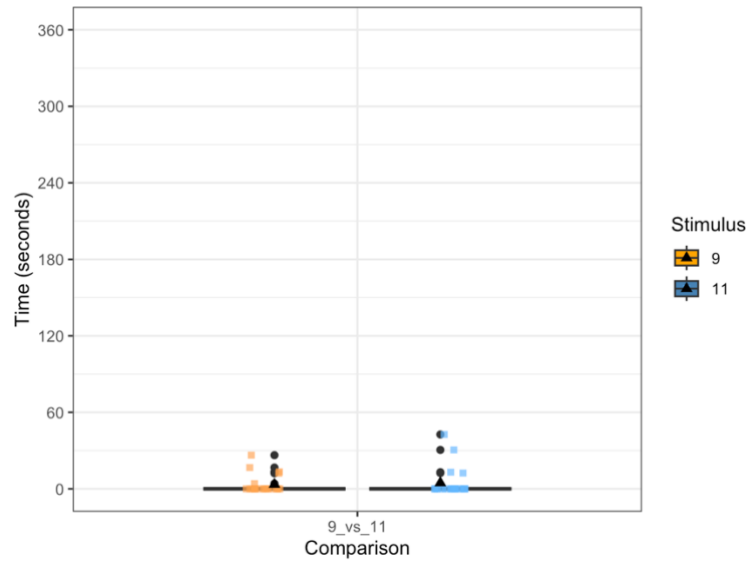


Figure 8

Second experiment: Time spent in proximity to each stimulus during the first minute starting after the subject's first choice, following habituation to white screen with a moving cross. The y-axis represents the time spent in proximity to each stimulus in seconds; the x-axis indicates the numerical comparison. Blue box denote time spent close to the prime numerosity (11); orange box denote time spent close to the composite numerosity (9). Black dots represent outliers; black triangles represent the mean.

4. Discussion

Our results revealed a spontaneous preference for the prime numerosity. This preference, however, was dependent on numerical magnitude. Specifically, results from the first experiment indicate that only the 7vs9 comparison yielded significant results, whereas 9vs11 failed to reach significance.

This observation could be explained by considering the numerical ratio, and hence Weber's Law, which states that numerical discrimination between two numerosities becomes increasingly complex as the ratio between the values approaches 1^[24]. Considering the comparisons employed in this research, the 7/9 ratio (0.77) is easier to discriminate than the 9/11 ratio (0.81)^[14]. The limits represented by Weber's Law in larger configurations could represent a boundary that prevents

subjects from properly discriminate between the two values, thus making it impossible for them to express a preference. This cognitive limit impairs also the potential utility of the cross-shaped attention-getter. Across both experiments (blank and cross habituation), 9vs11 configuration consistently yielded non-significant results, precluding any assessment of the attention-getter's role on the attention span of the subjects during testing.

A detailed evaluation of the temporal analysis performed is crucial for interpreting these behavioral data. In both experiments, results from the first minute following the initial choice mirrored perfectly the overall results of the 6-minute testing window. Isolating this early interval is essential to understand how the time spent in the arena affects the attention of subjects, allowing to differentiate an initial response from long-lasting behaviors that can be further affected by habituation or fatigue. Animals' attention biologically declines overtime and in this specific experiment, where the preference relies entirely on the chick's intrinsic motivation to explore the environment, an extended duration such as six minutes can lead to the subject's loss of interest or increased distress, hiding the original preference choice. The fact that the preference for the prime stimulus in the 7vs9 comparison was significant during the first minute as in the total time confirms that the chick choice was a direct spontaneous cognitive response to the stimuli and not the product of an extended random wandering in the environment following loss of engagement. Consequently, combining short-term and full-testing data strengthen the reliability of this research findings, ensuring the prime preference observed to be robust and not accidental.

Although we couldn't find a decisive preference toward prime numbers across all conditions, results obtained from this research are crucial in avian numerical cognition investigation. The lack of significance from the results involving 9vs11 comparison in both the experiments, highlights the limit represented by such large numerosities. As shown from previous research, similarly to humans, chicks appear to be slower in numerical processing as the size of the numerosity increases^[14]. For the same principles described above, 9 and 11 might represent numerosities large enough to trigger a drop in cognitive processing efficiency. Hypotheses have been proposed linking this phenomenon to a limit in working memory, specifically regarding the number of subsets that can be perceived at once. A strategy that should be explored to bypass this boundary in future research would be to enhance grouping already within the visual stimuli by pre-clustering the elements in subgroups or by

color grouping the different subsets, in both cases reducing cognitive load^[14]. This approach already proved to be effective in prior research involving the even more challenging comparison 13vs15. In this setting, the failure in discrimination between basic sets of numerosities, was restored through grouping strategy.^[14] Another route to escape this effect, would be to replicate the current study comparing smaller sets of numerosities, to exclude the role of numerical magnitude in overpowering the subjects' baseline ability to express a preference. Since sets of 9 and 11 elements have already been employed in previous research, a secondary approach might be to inquire into Weber's law, exploiting, as visual cues, comparisons with lower ratio. If the 9/11 ratio (0.81) is the determinant of the statistically non-significant preference result, due to complexity in discrimination of the two stimuli, employing lower ratios (e.g. 5vs9 or 9vs13) could represent an effective strategy.

One final essential point of inquiry is the role of habituation. Because the only numerical comparison present in both experiments conducted in the current research (9vs11) failed to provide significant results, we still cannot fully comprehend how a change in the habituation stimulus, from a blank screen to one provided with an attention-getter, influences the final choice during testing. Future studies should compare testing the same numerosities with a different habituation phase prior to testing, to definitely identify the weight of this methodological step. Nevertheless, results from the successful 7vs9 comparison in the first experiment yields a crucial finding: the preference toward prime numbers observed in research to date, is not merely the result of a response to novelty, driven by a phase of habituation to even numbers prior to testing, but is rather the product of an innate discrimination mechanism deeply rooted in avian mind. Obtaining a robust preference following a period of habituation to a blank screen, rather than an even numerosity is a fundamental step in excluding a simple novelty response, opening the way for new investigations up to explore this obscure intrinsic biological preference.

5. Conclusion

This research thesis provides substantial evidence that day-old chicks possess a spontaneous preference for prime, asymmetrical numerosities when presented with a 7vs9 choice. This cognitive capacity, however, is governed by numerical ratio: the absence of a preference at higher magnitudes

(9vs11) highlights the cognitive limit dictated by Weber's law and working memory. These results demonstrate that avian numerical cognition is bound by complex ratios: future investigations focusing on ratio limits will be crucial to shed light on spontaneous numerical discrimination in non-human animals. Crucially though, a major finding has been highlighted by this research results: chicks demonstrate a spontaneous preference for prime over composite numbers, independently of prior habituation. Because this preference persisted even when chicks were habituated to a blank screen rather than even numbers, the mechanism underlying their choice cannot be simply reconnected to a mere response to novelty. Instead, this finding strongly suggests an innate, biological disposition, entirely unconnected to the type of stimulus presented prior to testing. This conclusion opens new fundamental routes of investigation concerning a key inquiry: how deeply these mathematical mechanisms are embedded in the animal mind.

Bibliography

1. Lehmann-Ziebarth N, et al. Evolution of periodicity in periodical cicadas. *Ecology*. 2005;86:3200–11.
2. Williams KS, Simon C. The ecology, behavior, and evolution of periodical cicadas. *Annu Rev Entomol*. 1995;40:269–95.
3. Welling H. Prime number identification in idiots savants: can they calculate them? *J Autism Dev Disord*. 1994 Apr;24(2):199-207. doi: 10.1007/BF02172096. PMID: 8040161.
4. Ciccione L, Dehaene S. Grouping Mechanisms in Numerosity Perception. *Open Mind (Camb)*. 2020 Nov 1;4:102-118. doi: 10.1162/opmi_a_00037. PMID: 34485793; PMCID: PMC8412191.
5. Starkey GS, McCandliss BD. The emergence of “groupitizing” in children’s numerical cognition. *J Exp Child Psychol*. 2014;126:120–37
6. Geraci A, Loconsole M, Regolin L. A symmetry-based mechanism for perceptual grouping in preverbal infants. *Sci Rep*. 2025 Feb 11;15(1):5035. doi: 10.1038/s41598-024-83251-4. PMID: 39934171; PMCID: PMC11814068.
7. Xu F, Spelke ES, Goddard S. Number sense in human infants. *Dev Sci*. 2005 Jan;8(1):88-101. doi: 10.1111/j.1467-7687.2005.00395.x. PMID: 15647069.
8. Xu F, Spelke ES. Large number discrimination in 6-month-old infants. *Cognition*. 2000 Jan 10;74(1):B1-B11. doi: 10.1016/s0010-0277(99)00066-9. PMID: 10594312.
9. Rugani R, Vallortigara G, Regolin L. From small to large: Numerical discrimination by young domestic chicks (*Gallus gallus*). *J Comp Psychol*. 2014;128(2):163–71. <https://doi.org/10.1037/a0034513> PMID: 24188620
10. Rugani R, Cavazzana A, Vallortigara G, Regolin L. One, two, three, four, or is there something more? Numerical discrimination in day-old domestic chicks. *Anim Cogn*. 2013;16(4):557–64. <https://doi.org/10.1007/s10071-012-0593-8> PMID: 23334508

11. Rugani R, Fontanari L, Simoni E, Regolin L, Vallortigara G. Arithmetic in newborn chicks. *Proc Biol Sci.* 2009;276(1666):2451–60. <https://doi.org/10.1098/rspb.2009.0044> PMID: 19364746
12. Rugani R. 2017 Towards numerical cognition's origin: insights from day-old domestic chicks. *Phil. Trans. R. Soc. B* 373:20160509.
13. Loconsole M, Tedaldi E, Regolin L (2026) Distinct early-life mechanisms of quantity discrimination in domestic chicks. *PLoS One* 21(5): e0349870.
14. Loconsole M, De Agro M, Regolin L. 2021 Young chicks rely on symmetry/asymmetry in perceptual grouping to discriminate sets of elements. *Proc. R. Soc. B* 288: 20211570.
15. Clara E, Regolin L, Vallortigara G. Preference for symmetry is experience dependent in newborn chicks (*Gallus gallus*). *J Exp Psychol Anim Behav Process.* 2007 Jan;33(1):12-20. doi: 10.1037/0097-7403.33.1.12. PMID: 17227191.
16. Loconsole M, Regolin L. Are prime numbers special? Insights from the life sciences. *Biol Direct.* 2022 May 27;17(1):11. doi: 10.1186/s13062-022-00326-w. PMID: 35619145; PMCID: PMC9137056.
17. Jackson PS, Bateson PPG. Imprinting and exploration of slight novelty in chicks. *Nature.* 1974;251:609–10.
18. Jones RB, Larkins C, Hughes BO. Approach/avoidance responses of domestic chicks to familiar and unfamiliar video images of biologically neutral stimuli. *Appl Anim Behav Sci.* 1996;48:81–98. [https://doi.org/10.1016/0168-1591\(95\)01003-3](https://doi.org/10.1016/0168-1591(95)01003-3)
19. Friard O, Gamba M. BORIS: A free, versatile open-source event-logging software for video/audio coding and live observations. *Methods Ecol Evol.* 2016;7(11):1325–30. <https://doi.org/10.1111/2041-210x.12584>
20. R Core Team. R: A language and environment for statistical computing. Vienna, Austria: R Foundation for Statistical Computing. 2019.
21. Spatial-Numerical Association in Nonhuman Animals. *The Cambridge Handbook of Animal Cognition*, 2021, pp. 620–602, <https://doi.org/10.1017/9781108564113.032>.
22. Rugani R, Vallortigara G, Priftis K, Regolin L. Response: "Newborn chicks need no number tricks. Commentary: Number-space mapping in the newborn chick resembles humans' mental

23. number line". *Front Hum Neurosci.* 2016 Feb 5;10:31. doi: 10.3389/fnhum.2016.00031. PMID: 26903839; PMCID: PMC4742540.
24. Rogers LJ. Evolution of hemispheric specialization: advantages and disadvantages. *Brain Lang.* 2000 Jun 15;73(2):236-53. doi: 10.1006/brln.2000.2305. PMID: 10856176.
25. Worsley MZ, Schroeder J, Dixit T. How animals discriminate between stimulus magnitudes: a meta-analysis. *Behav Ecol.* 2025 Mar 24;36(3):araf025. doi: 10.1093/beheco/araf025. PMID: 40342796; PMCID: PMC12059214.