Do early environmental experiences impact numerical discrimination abilities in a lizard?

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## Abstract

From social behaviour to navigating complex environments, quantitative abilities can be crucial to fitness. Early life conditions can impact brain development to affect quantitative competence. In anthropogenically modified environments, early thermal conditions or glucocorticoid concentrations (GCs) – stress-related hormones transmitted by the parents – can play a prominent role in shaping cognition through their effects on brain physiology. Furthermore, temperature can lead to increased levels of GCs that are passed on to offspring, emphasizing the need to study the combined effects of these two factors. Here, we investigated the effects of elevated prenatal corticosterone (CORT) – the main GC in reptiles – and incubation temperature on numerical discrimination in the common garden skink (*Lampropholis guichenoti*). We then assessed numerical abilities through a spontaneous choice test with food as the relevant stimulus. Employing a repeated measures design, we subjected lizards to five numerical tests each differing in the ratios between the two choices (1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 2 VS 4). Contrary to our expectations, we found no evidence for treatment effects on lizard behaviour and no use of numerical discrimination during foraging in *L. guichenoti*. Our findings align with previous studies indicating that reptiles feeding on live prey may have difficulty distinguishing between different prey quantities in spontaneous choice tests.

## Significance statement

Discriminating between quantities can be crucial for individual fitness, yet the impact of early environmental factors on the development of quantitative competence remains largely unexplored. In this study, we investigated, for the first time, the effects of prenatal corticosterone exposure and incubation temperature on numerical discrimination in a reptile. Contrary to our predictions, we did not observe any evidence of numerical discrimination and therefore no impact of early developmental environment. Our results align with previous studies showing that reptiles consuming live prey struggle to differentiate prey numbers in spontaneous choice tests. These results open new avenues for exploring the evolution of numerical abilities in reptiles and identifying factors influencing the development of quantitative skills in this group. Further research should explore alternative methods, such as trained tasks, to better understand the cognitive mechanisms underlying quantitative competence in reptiles.

## Introduction

The ability to discern between quantities is a fundamental cognitive skill widely observed across the animal kingdom ([Vonk and Beran 2012](#ref-vonk2012bears); [Stancher et al. 2015](#ref-stancher2015numerical); [Beran and Parrish 2016](#ref-beran2016capuchin)). Numerical cognition can contribute to social decisions, mate selection, and foraging behaviour, which can be adaptive in various ecological contexts ([Lucon-Xiccato and Dadda 2017](#ref-lucon2017individual); [Nieder 2018](#ref-nieder2018evolution)). For instance, female lions (*Panthera leo*) use numerical information to assess the risk of confronting rival groups ([McComb et al. 1994](#ref-mccomb1994roaring)), male adult mealworms (*Tenebrio molitor*) select sites with scents of more females ([Carazo et al. 2009](#ref-carazo2009quantity)), and red-backed salamanders (*Plethodon cinereus*) prefer tubes containing larger numbers of prey ([Uller et al. 2003](#ref-uller2003salamanders)). Given the adaptive advantages of numerical and quantity discrimination, research has focused extensively on exploring the ability of different species to differentiate between quantities under different contexts and paradigms.

Numerical competence is often evaluated by considering the types of cues animals use ([Plotnik et al. 2019](#ref-plotnik2019elephants); [Cooper et al. 2024](#ref-cooper2024tell)), the ecological contexts in which these abilities are deployed ([McComb et al. 1994](#ref-mccomb1994roaring); [Chittka and Geiger 1995](#ref-chittka1995can); [Uller et al. 2003](#ref-uller2003salamanders); [Carazo et al. 2009](#ref-carazo2009quantity)), and the neural mechanisms that underlie them ([Nieder 2005](#ref-nieder2005counting)). The latter have demonstrated that non-verbal numerical representations in mammals activates an extensive neural pathway including regions involved in eye movement, attention control, or complex learning ([Nieder 2005](#ref-nieder2005counting)). The connection between numerosity and brain physiology underscores the importance of understanding how brain development influences numerical abilities.

Brains are particularly sensitive to environmental inputs during early stages of development ([Coomber et al. 1997](#ref-coomber_independent_1997); [Zhu et al. 2004](#ref-zhu_prenatal_2004)), with long-lasting effects on cognitive abilities ([Zhu et al. 2004](#ref-zhu_prenatal_2004); [Amiel et al. 2014](#ref-amiel_egg_2014)). For instance, glucocorticoids (GCs), steroid hormones that mediate the physiological stress response ([Sapolsky et al. 2000](#ref-sapolsky_how_2000)), can alter performance in spatial, associative, or reversal learning tasks if elevated during early stages of development ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004); [Crino et al. 2014](#ref-crino_corticosterone_2014-learn); [Farrell et al. 2015](#ref-farrell_developmental_2015-learn); [Bebus et al. 2016](#ref-bebus_associative_2016); [Lui et al. 2017](#ref-lui2017chronic)). In ectotherms, temperature can affect GC levels in parents to affect developing offspring (i.e., maternal effects ([Jessop et al. 2016](#ref-jessop2016multiscale); [Racic et al. 2020](#ref-racic_effects_2020); [Mentesana and Hau 2022](#ref-mentesana2022glucocorticoids); [Crino et al. 2023](#ref-Crino_2023)). Prenatal exposure to GCs is typically associated with impaired learning skills, but these effects have been shown to vary depending on factors such as dose, sex, or type of cognitive test employed ([Szuran et al. 1994](#ref-szuran_water_1994); [Farrell et al. 2015](#ref-farrell_developmental_2015-learn); [Bebus et al. 2016](#ref-bebus_associative_2016); [Haq et al. 2021](#ref-haq_prenatal_2021)). Nevertheless, little is known about how exposure to GCs during development can affect quantitative abilities.

The effects of prenatal GCs on learning may be modulated by other developmental effects or environmental conditions. For example, the early thermal environment plays a prominent role in brain development and cognitive abilities in ectotherms ([Coomber et al. 1997](#ref-coomber_independent_1997); [Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Amiel et al. 2017](#ref-amiel_effects_2017); [Vila Pouca et al. 2018](#ref-vila_pouca_incubation_2018), [2019](#ref-vila_pouca_quantity_2019)). In lizards, incubating eggs at elevated temperatures improves cognitive abilities consistent with elevated neuronal density in some areas of the brain ([Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Amiel et al. 2017](#ref-amiel_effects_2017)), but impairs cognition at extreme temperatures ([Dayananda and Webb 2017](#ref-dayananda_incubation_2017); [Abayarathna and Webb 2020](#ref-abayarathna_effects_2020)). In addition, when Vila Pouca et al. ([2019](#ref-vila_pouca_quantity_2019)) tested the effects of elevated incubation temperature on numerical discrimination in Port-Jackson sharks (*Heterodontus portusjacksoni*) and found that sharks incubated at elevated temperatures learned faster in a quantity discrimination task ([Vila Pouca et al. 2019](#ref-vila_pouca_quantity_2019)). However, the effects of early thermal environment on numerical abilities in other taxa remains largely unexplored.

Early-life GCs and thermal conditions could have interactive effects that influence cognitive development. Understanding how these factors influence quantitative abilities could reveal important insights into the ecological relevance of numerosity. Given the influence of numerical cognition on fitness, we would expect evolutionary pressures to be similar across taxa, and yet, research on numerical discrimination has been traditionally focused on mammals, birds, and fishes ([Nieder 2005](#ref-nieder2005counting); [Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). However, recent studies demonstrate that reptiles are also competent in numbers. For example, red-footed turtles (*Chelonoidis carbonaria*) rapidly learned to associate colour with higher volumes of food ([Soldati et al. 2017](#ref-soldati2017long)), Hermann’s tortoises (*Testudo hermanni*) discriminate between large and small food quantities in a spontaneous choice test ([Gazzola et al. 2018](#ref-gazzola2018continuous)), and freshwater turtles (*Trachemys scripta* and *Mauremys sinensis*) rapidly learned a quantity discrimination task ([Lin et al. 2021](#ref-lin2021superior), [2024](#ref-lin2024trained)). The italian wall lizard (*Podarcis siculus*) failed to discriminate between different numbers of food items in a spontaneous choice test ([Miletto Petrazzini et al. 2017](#ref-miletto2017quantitative)), but succeeded in a trained quantity discrimination task ([Miletto Petrazzini et al. 2018](#ref-miletto2018quantity)). In contrast, Iberian rock lizards (*Iberolacerta cyreni*) preferred larger quantities of crickets when presented five versus ten items ([Recio et al. 2021](#ref-recio_prey_2021)). Indeed, the literature shows evidence for basic quantitative abilities in reptiles that may vary with the type of cue and the test employed.

Here, we investigated the effect of prenatal corticosterone (CORT) - the main GC in reptiles - and incubation temperature on numerical discrimination in a lizard. We manipulated CORT concentration (CORT-treated or a sham control) in *L. guichenoti* eggs and incubated them under one of two temperature regimes (Cold - 23 ± 3ºC or Hot - 28 ± 3ºC) in a 2x2 factorial design. Then, we assessed numerical discrimination abilities of lizards unsing a spontaneous choice test approach. The numerical discrimination task consisted of five tests that differed in the relative number of food items: 1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4 crickets. We based this experiment on observations in nature that the ability to detect a change in stimulus intensity depends on the relative, not absolute, difference between the stimuli [‘Weber’s law’; Agrillo and Bisazza ([2014](#ref-agrillo2014spontaneous))]. Built upon other studies that explored the cognitive effects of prenatal GCs or thermal early environment in reptiles and other taxa, we hypothesized that lizards incubated at higher temperatures would outperform those incubated at lower temperatures in the numerical discrimination task ([Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Amiel et al. 2017](#ref-amiel_effects_2017); [Vila Pouca et al. 2019](#ref-vila_pouca_quantity_2019)). We predicted that increased CORT levels would impair numerical competence ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004)), with more pronounced effects at lower temperatures. Consistent with Weber’s law, we predicted that lizards incubated at higher temperatures would successfully discriminate between quantities even at high ratios (e.g. 3 VS 4), whereas even the lowest ratios (e.g. 1 VS 4) could be challenging for those exposed to CORT or incubated at lower temperatures.

## Methods

#### Animal husbandry

*Breeding colony* – The lizards tested in our experiment came from a breeding colony established in the lab in 2019. The colony consisted of approximately 180 adults of *L. guichenoti* housed in communal containers (41.5 L x 30.5 W x 21 H cm) with six lizards (2 males and 4 females) per enclosure. Enclosures were provided with non-stick matting, shelter, and several small water dishes filled daily, and lizards were fed mid-size crickets (*Acheta domestica*) three days a week. Crickets were dusted with calcium weekly and multivitamins and calcium biweekly. Room temperatures were set to 22-24ºC, but to ensure a temperature gradient, we employed a heat chord and a heat lamp following a 12 h light:12 h dark cycle, keeping the warm side of enclosures at 32-34ºC.

*Egg collection and incubation* – Between mid-October 2023 to the end of February 2024, we placed small boxes (12.5 L x 8.3 W x 5 H cm) containing vermiculite on one side of the communal enclosures (see above) to provide females with a place to lay the eggs. We checked for eggs in the boxes three days a week. Egg length and width were measured with a digital calliper to the nearest mm (± 0.1 mm), while mass was recorded with a digital scale (OHAUS, Model spx123) to the nearest g (± 0.001 g). Eggs were assigned a clutch number and an individual identity. Then we treated eggs with CORT or a vehicle control (see *Manipulating Early Thermal and CORT Environments* details below) and placed them in individual cups (80 mL) with moist vermiculite (12 g water to 4 g vermiculite). We covered the cups with plastic wrap to retain moisture and left the eggs in incubators (LATWIT 2X5D-R1160) programmed to two different thermal regimes (see *Manipulating Early Thermal and CORT Environments* details below) until hatching. Incubators were checked for the presence of hatchlings three times a week.

*Hatchlings* – Immediately after hatching, we measured Snout-Vent Length (SVL) and Tail Length (TL) with a ruler to the nearest mm (± 0.1 mm), and mass using a digital scale (OHAUS, Model spx123) to the nearest g (± 0.001 g). Hatchlings were then placed in individual enclosures (18.7L x 13.2W x 6.3H cm) provided with non-stick matting and a small water dish. During this period, they were given water daily and received 3-6 small *A. domestica* crickets three times a week. All care otherwise follows similar protocols to adults (see above).

#### Manipulating Early Thermal and CORT Environments

We manipulated CORT concentration in eggs and incubated them under one of two temperature regimes (Cold – 23 ± 3 ºC or Hot – 30 ± 3 ºC) in a 2x2 factorial design ([Fig. 1](#fig-Methods) A). Eggs were allocated to one of two different developmental stress treatments: CORT-treated eggs were topically supplied with 5 µL of a CORT solution (10 pg/mL). Control treatment eggs received an equal volume of 100% Ethanol. Corticosterone treatments were made by dissolving crystalline corticosterone (Sigma, Cat. No. C2505) in 100% ethanol. We selected doses based on previous studies where CORT treatment increased mean yolk CORT levels ~3.7x higher than control eggs in *Lampropholis delicata* ([Crino et al. 2024](#ref-crino2024eggs)). Then, eggs were incubated in one of the two previously mentioned temperature regimes (Cold or Hot) until hatching. These temperatures represent the upper and lower limit of the natural incubation temperatures for this species ([Qualls and Shine 2000](#ref-qualls2000post)).

The number of eggs per clutch assigned to each hormone and temperature treatment was counterbalanced in a partial split-clutch design. At least one egg per clutch to each treatment, and the remaining eggs were randomly assigned to one of the treatments. When we found less than four eggs in a cluthc, we assigned each egg randomly to one of the treatments.

#### Numerical discrimination task

Two weeks before starting the numerical discrimination task (see below), lizards were moved to the experimental arenas for acclimatisation. The arenas were individual medium-size (41 L x 29.7 W x 22 H cm) plastic containers provided with a shelter (9 L x 6 W x 1.5 H cm) on one of the sides and a water dish in the center ([Fig. 1](#fig-Methods) B). Arenas were placed on seven different racks located in two experimental rooms. Each rack was associated with its own CCTV system (device model DVR-HP210475), allowing us to record lizards’ behaviour during the experiment. Despite the conditions in the experimental rooms were the same as in the colony room, we counterbalanced the number of lizards per treatment in each rack to control for any potential effects of the room or the position of the lizard in the rack. During acclimatisation and throughout the experiment, lizards were fed with only one cricket daily, dusted with calcium and multivitamins (see protocol below), and water was supplied *ad libitum*. The temperature of both rooms was set to 22-24ºC, but we also provided a temperature gradient (24-32°C) using a heat cord along the center of the arena and heat lamps in a 12 h light: 12 h dark cycle.

The numerical discrimination test consisted of a series of two-choice trials where lizards were presented with different numbers of food items. Each choice was placed on one of the two lateral platforms of a white 3D printed device (see [Fig. 1](#fig-Methods) B, C) and then covered with a transparent Petri dish to prevent the lizard from obtaining the food. We performed five tests that differed in the ratio between both choices of crickets. Specifically, we compared: 1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4 crickets. The food consisted of small frozen crickets (*A. domestica*) that were thawed and dusted with calcium and multivitamins. We decided to use frozen crickets to avoid movement that would affect lizard behaviour ([Cooper et al. 2024](#ref-cooper2024tell)).

Lizards were fed frozen crickets for one month prior to the experiments to habituate them to eating frozen prey. To habituate lizards to the experimental conditions, frozen crickets were placed on top of one of the platforms and Petri dishes during each feeding for two weeks prior to experimental trials. The side where the food was placed was changed every day to avoid any side bias during the trials. However, to further control for side biases, the higher number of crickets was randomly placed on the right or the left platform. We also counterbalanced the number of individuals per treatment tested in the same type of trial each day.

The crickets used during the experiment were all the same size, but to control for other quantitative traits we changed the orientation of the crickets as illustrated in [Fig. 1](#fig-Methods) D. This approach created a conflict of information between choices, as horizontally oriented crickets could occupy the same space as a greater number of vertically oriented crickets. This allowed us to determine whether the lizards relied on discrete numerical units rather than non-numerical cues, such as total length, area, or volume ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). In addition, after the experiments, we conducted another set of trials to test whether the orientation of the crickets could affect lizards’ choice, but we found no effect of orientation (see *Supplementary Material - Prey orientation test*).

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| Fig 1— Experimental design. Panel (**A**) shows the early environment manipulation procedures. (**B**) illustrates the arena where the tests were performed, while panel (**C**) indicates the measurements of the platform used for the experiments. Finally, panel (**D**) displays the types of numerical tests used and the orientation of the crickets in each test. |

All tests were done between 1000-1200 hours when the lizards were most active. Each trial was performed daily for five days between the 17th and 22nd of May 2024. We recorded three main variables: i) *Latency*, defined as the time between the start of the test - when the platform was left in the enclosure - until the first interaction with one of the options; ii) First choice of the lizard (*Choice*), recorded as 1 if the lizard interacted first with the larger amount or 0 if not; and iii) *Interest* shown for the higher amount of food (detailed below). We considered that the lizard interacted with the food when it touched the Petri dish with its snout or when the front half of the body was on top of the platform. For five minutes after the first interaction with one of the options, we recorded the time spent interacting with that option for a maximum of five minutes; we did this for both amounts of food independently of what was the first choice. We measured the interest shown for the higher amount of food (*Interest*) by subtracting the time interacting with the option with fewer crickets to the time spent interacting with the larger amount of food. If there was no interaction with one of the options during the test, we considered the time spent as zero for that option. When there was no interaction with any of the choices, both *Latency*, *Choice*, and *Interest* were noted as NA. We also considered Interest as NA in a few cases where the animals managed to lift the dish and eat the prey; Latency and Choice were recorded and employed in the analyses. We excluded from the analyses all the individuals that did not make any choice in three or more tests.

Motivation plays a key role in animals’ performance in spontaneous choice tests ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous); [Bisazza et al. 2014](#ref-bisazza2014experim)). To ensure that lizards remained motivated to forage, they were provided with only one cricket during both acclimatization and the numerical task (see above). During acclimatization, lizards were fed at the same time each day as the experiments were conducted. In the numerical task, lizards received a cricket immediately after the test and then fasted for more than 20 hours, which we expected would help standardize fasting levels across individuals. To further control for motivation, we excluded from our analyses any trials in which lizards did not interact with any options or did not eat the cricket provided after the test (n = 0 in both cases). Consequently, we do not consider motivation to be a major factor influencing our results (but see Discussion).

#### Statistical analyses

In our analyses, we fitted a multivariate Bayesian multilevel model using the brm function from the *brms* package ([Bürkner 2017](#ref-burkner2017brms)) in R (version 2.8.2) ([R Core Team 2021](#ref-R)). We ran four parallel MCMC chains of 3000 iterations for each model, with a warmup period of 1000 iterations. We checked that all MCMC chains converged (Rhat < 1.2) and were mixing effectively to ensure we had >1000 effective samples from the posterior distribution.

We modelled the three main recorded behaviours: *Latency*, *Choice*, and *Interest* as the response variables. We assumed normal distributions for Latency (log-transformed) and Interest [family = gaussian()]. The error structure for Choice was modeled using a Bernoulli distribution with a logit link function [family = Bernoulli(link = ‘logit’)]. We included test (1 VS 4, 1 VS 3, 2 VS 4, 2 VS 3, 3 VS 4), hormone (CORT versus Control), incubation temperature (Cold versus Hot), and the three-way interaction as fixed factors. We also included in our predictors sex, and age. We did not find any effect of sex or age on Choice or Interest, but we found an effect on Latency (see Results). Regardless, we included both factors in all models. Age was centered to zero in the model, and we averaged the predicted values for males and females.

We included lizard identity and clutch as random factors. *L. guichenoti* lays up to two clutches per year ([Joss and Minard 1985](#ref-joss1985reproductive)). Since egg collection was done during half of the breeding season, each clutch likely came from a unique mother, and so, clutch identity captures potential maternal effects.

We used the posterior distributions of parameters from these models to test for between treatment differences in the ability to discriminate different numbers of crickets for each of the numerical tests. Because the posterior distributions were not always normally distributed, we report the median as the main measure of central tendency. We used the 95% Highest Posterior Density Intervals (95% HPDI) using the hdi function in bayestestR ([Makowski et al. 2019](#ref-bayestestR)) to test if the contrasts between treatments for all the variables, or the *Interest* per each test was different form zero. Given Choice was Bernoulli, we modified our null hypotheses to test if differed from a probability of 0.5 as there were only two possible choices and if animals were choosing randomly we would predict each choice would have a 50% probability.

#### Ethical note

Subjects were collected from a breeding colony that had been kept in the lab since 2019. All animals in this experiment were provided humane laboratory housing, thermoregulation opportunities, and light and humidity conditions (see above for details). Lizards in the colony received five to seven crickets per individual three times a week while the subjects in the experiment were fed once per day. All lizards were handled minimally to avoid stress. Experimental procedures and laboratory housing complied with Australian law and were approved by the Australian National University Animal Experimentation Ethics Committee (A2022\_33). Upon completion of experimental trials, lizards were kept in their enclosure and will be euthanized following standard humane procedures once they reach the humane endpoint.

## Results

Overall, males showed lower latencies than females (median of the estimated effect of sex = -0.45, 95% HPDI = [-0.89, -0.02]), and older individuals also made decisions faster (mean estimated effect of age = 0.06, 95% HPDI = [0.01, 0.11]; see Table S3 in *Supplementary Material*). However, we did not see any effect of age or sex on *Choice* or *Interest* (see *Supplementary Material*).

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| Fig 2— Estimates of log-latency (Latency), the probability of choosing the larger number of crickets first (Choice), and the estimated interest in the larger number of crickets (Interest) for each of the numerical tests performed across different developmental treatments. The x-axis represents the estimate, and the y-axis is the posterior density of the estimates. The different colours indicate the different treatments. Points and bars represent the median and 95% Higest Density Intervals (95% HPDI) of the estimates, respectively. Vertical dashed lines in Choice and Interest graphs values 0.5 and 0, respectively. Asterisks indicate values significantly different from 0. |

Neither temperature, CORT, or their interaction affected performance in any of the tests, nor were there any clear patterns suggestive of an effect of the developmental environment on numerical discrimination (see Table 1 and [Fig. 2](#fig-results)). Except for Hot-CORT lizards in 1 VS 3 tests or Cold-Control lizards in 2 VS 3 tests, the predicted probability of choosing the larger number of crickets first was not different from 0.5 ([Fig. 2](#fig-results); but also see Table S1 and Table S2 in *Supplementary Material*). Similarly, interest in the larger number of crickets (*Interest*) was not different from 0 in any of the tests ([Fig. 2](#fig-results); but also see Table S1 and Table S2 in *Supplementary Material*).

*Table 1. Effects of temperature, CORT, and their interaction on Latency, Choice, and Interest in each of the numerical discrimination tests. The table shows the contrasts for each predictor (Temperature = [medianHot - medianCold]; Hormone = [medianControl - medianCORT]; and their Interaction = [(medianHot-Control - medianHot-CORT) - (medianCold-Control - medianCold-CORT)]). 95% Higest Density Intervals (95% HPDI) test the hypothesis that contrasts are different from zero.*

|  | | Tests | | | | |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Predictor | 1VS4 | 1VS3 | 2VS4 | 2VS3 | 3VS4 |
| Latency | Hormone | -0.3 [-1.4 , 0.78] | -0.1 [-1.13 , 0.83] | 0 [-1 , 0.94] | -0.2 [-1.08 , 0.77] | -0.3 [-1.17 , 0.52] |
| log(latency) | Temperature | -0.3 [-1.45 , 0.75] | -0.2 [-1.22 , 0.73] | -0.4 [-1.35 , 0.58] | -0.4 [-1.34 , 0.53] | -0.1 [-0.89 , 0.81] |
|  | Interaction | -0.8 [-1.96 , 0.41] | -0.5 [-1.73 , 0.67] | -0.5 [-1.73 , 0.64] | -0.4 [-1.62 , 0.77] | 0 [-1.2 , 1.2] |
| Choice | Hormone | 0 [-0.46 , 0.43] | 0 [-0.42 , 0.54] | 0 [-0.34 , 0.41] | 0.1 [-0.36 , 0.45] | 0.1 [-0.26 , 0.47] |
| log(odds) | Temperature | 0.1 [-0.34 , 0.53] | 0.2 [-0.29 , 0.65] | 0 [-0.37 , 0.38] | -0.3 [-0.66 , 0.15] | 0.2 [-0.21 , 0.52] |
|  | Interaction | -0.3 [-0.81 , 0.19] | -0.4 [-0.87 , 0.05] | 0.1 [-0.42 , 0.61] | -0.2 [-0.7 , 0.27] | -0.1 [-0.62 , 0.36] |
| Interest | Hormone | -1.3 [-59.51 , 55.55] | -11.9 [-86.56 , 60.62] | 1.2 [-61.97 , 64.86] | 2.9 [-77.38 , 82.81] | 40.3 [-20.63 , 99.28] |
|  | Temperature | -11.5 [-69.12 , 44.05] | 22.4 [-51.54 , 95.43] | -5.2 [-68.39 , 57.85] | -22.2 [-104.38 , 56.45] | 3.7 [-56.06 , 63.76] |
|  | Interaction | 19.5 [-58.38 , 92.19] | -56 [-134.41 , 20.47] | 35 [-41.16 , 112.34] | -69.6 [-145.25 , 8.58] | -23.6 [-102.28 , 54.29] |

**?(caption)**

## Discussion

Contrary to our predictions that numerical cues would influence foraging decisions, and that elevated prenatal CORT or cold incubation temperatures would impair numerical discrimination, we found no significant differences across tests or treatments. Our results indicate that lizards did not discriminate between different numbers of crickets, nor did their performance vary under our experimental conditions. Overall, these findings suggest that *L. guichenoti* did not use numerical or other potential quantitative cues for foraging decisions.

#### Foraging context may influence prey number discrimination in reptiles

Lack of numerical discrimination in *L. guichenoti* may be due to insectivorous lizards relying on other cues, such as movement or size, for foraging decisions. In studies where reptiles discriminated between different amounts of food, the relevant stimuli involved either vegetables ([Gazzola et al. 2018](#ref-gazzola2018continuous); [Szabo et al. 2021](#ref-szabo_spontaneous_2021)) or large quantities (e.g., 5 vs. 10)([Recio et al. 2021](#ref-recio_prey_2021)). In contrast, when *Podarcis siculus* were presented different numbers of *Musca domestica* larvae in a spontaneous choice test, the lizards failed to discriminate between quantities despite showing high quantitative skills when prey size was the main cue ([Miletto Petrazzini et al. 2017](#ref-miletto2017quantitative)) or when tested using training procedures ([Miletto Petrazzini et al. 2018](#ref-miletto2018quantity)). Remarkably, the numbers of food items employed in Miletto Petrazzini et al. ([2017](#ref-miletto2017quantitative)) were always fewer than four. Spontaneous choice tests assume that animals should select the most appropriate quantity, which may not necessarily be the largest one ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). This occurrs if the costs of selecting the larger option outweigh the benefits. For example, when presented two groups with different numbers of conspecifics or if prey handling costs are related to larger quantitative traits like size ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous)). It could be that the perceived handling costs of larger numbers of prey is affecting lizard response in our study. Nevertheless, in that scenario, we would still expect animals to exhibit a preference, even if for the smaller amount of food, or to observe some influence of lizard size on their choices, as larger animals may be more adept at handling a greater number of prey items. Miletto Petrazzini et al. ([2017](#ref-miletto2017quantitative)) did not report any effect of body size, and age - a proxy for size - did not affect *L. guichenoti*’s *Choice* or *Interest* in our study. The absence of preference in *P. siculus* and *L. guichenoti* suggests that the benefits of selecting a larger number of prey are not different from selecting fewer. For instance, when considering hunting groups of 1 VS 4 or 2 VS 4 crickets, the probability of success might be similar. Furthermore, while one individual handles a prey item in the patch, other conspecifics could capture the rest. As a result, insectivorous lizards might not have evolved a preference for larger patches of prey, at least with small numbers (see [Recio et al. 2021](#ref-recio_prey_2021)).

Conversely, our findings may be influenced by the experimental design. In our study, we rotated the position of the crickets in the choice with fewer items to create a situation where the numbers and other quantitative cues associatied with numerosity were in conflict. This approach was intended to control for other quantitative cues that could be used by lizards to make decisions ([Cooper et al. 2024](#ref-cooper2024tell)). However, this manipulation could have made the task more challenging for lizards, potentially affecting their performance. Indeed, it is possible that *L. guichenoti* uses multiple quantitative cues simultaneously during foraging decisions. When those cues conflict, the preference for one cue over another might vary between individuals, potentially producing the results observed here. Future studies should explore the use of other quantitative cues in *L. guichenoti* and how they interact with numerical information. Such studies would enhance our understanding of how *L. guichenoti* integrates different quantitative cues during foraging, providing insights into their decision-making processes and overall quantitative abilities.

#### Foraging behaviour is robust to early environmental experiences

Although the effects of early environment on cognition is widely studied, little attention has been paid to its impacts on numerical discrimination. To the best of our knowledge, there is only one study examining how developmental conditions influence numerical abilities ([Vila Pouca et al. 2019](#ref-vila_pouca_quantity_2019)). Given the potent effects of early environment on cognition and brain development ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004); [Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Lui et al. 2017](#ref-lui2017chronic); [Amiel et al. 2017](#ref-amiel_effects_2017)), it is crucial to explore how early environmental conditions shape numerical abilities across taxa.

In our experimental design, prenatal treatments did not influence numerical discrimination in *L. guichenoti*, but we cannot discount the possibility that early environmental factors may affect numerical discrimination under other approaches or contexts. Based on previous studies showing the effects of prenatal temperature and GCs on cognitive abilities in reptiles and other groups ([Szuran et al. 1994](#ref-szuran_water_1994); [Zhu et al. 2004](#ref-zhu_prenatal_2004); [Amiel and Shine 2012](#ref-amiel_hotter_2012); [Clark et al. 2014](#ref-clark_colour_2014); [Amiel et al. 2014](#ref-amiel_egg_2014); [Lui et al. 2017](#ref-lui2017chronic); [Amiel et al. 2017](#ref-amiel_effects_2017)), we predicted that lower incubation temperatures and exposure to CORT will impair lizards’ performance, especially in those tests with higher ratios ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous); [Nieder 2018](#ref-nieder2018evolution)). However, we did not find any effect of the experimental treatments on *L. guichenoti*’s behaviour when tested in a numerical task. Both GCs and thermal environment can exert differential effects on distinct areas of the brain. For example, incubating eggs of the eastern three-lined skink (*Bassiana dupeyerri*) at elevated temperatures increased cell density in the medial cortex - linked to learning process and memory - but did not impact cell density in other nuclei ([Amiel et al. 2017](#ref-amiel_effects_2017)). Similarly, impairments in spatial learning in rats ([Haq et al. 2021](#ref-haq_prenatal_2021)) are likely associated with the greater density of GCs receptors in the hippocampus compared to other regions of the brain ([Siegel 2006](#ref-siegel_2006)). Researchers have proposed that non-verbal number representation is processed by two types of systems: one for small sets (≤ 4) that tracks and encodes objects as individual entities, and another for larger numerosities that operate through estimation processes ([Nieder 2005](#ref-nieder2005counting); [Cantlon et al. 2009](#ref-cantlon2009beyond); [Hyde 2011](#ref-hyde2011two)). While it remains unknown which areas of the reptiles’ brain encode numerical information, our results suggest that those brain regions involved in discrete numerical representation (≤ 4 items) might be robust to the effect of prenatal CORT and temperature in *L. guichenoti*.

Alternatively, it is plausible that treatment effects are masked by the overall poor performance across most of the tests, which could be a consequence of the species’ reliance on other types of cues for foraging other than numerical information. In this regard, motivation is a key factor in spontaneous choice tests ([Agrillo and Bisazza 2014](#ref-agrillo2014spontaneous); [Bisazza et al. 2014](#ref-bisazza2014experim)). Both developmental CORT and incubation temperature can affect metabolic rate (hereafter MR) which could affect motivation in food based learning paradigms ([Crino et al. 2014](#ref-crino_corticosterone_2014-learn); [Noble et al. 2018](#ref-noble_developmental_2018); [Cossin-Sevrin et al. 2022](#ref-cossin2022effect)). Although still possible, this explanation is less likely in our study because we controlled for motivation by providing only one cricket per day and fasting lizards for more than 20 hours before the test. In addition, we excluded tests where lizards did not interact with any of the options or did not eat the cricket provided after the test. Further studies should explore the effects of prenatal conditions on motivation and how it may affect the outcome of cognitive choice tests in reptiles.

#### Conclusion

Our study is, to the best of our knowledge, the first to explore the impact of prenatal conditions on numerical abilities in reptiles. Our findings suggest that *L. guichenoti* does not rely on numerical information for foraging decisions and that their performance does not vary across different prenatal treatments. These results indicate that early environmental conditions, such as incubation temperature and CORT exposure, may not affect numerosity in this species. However, it is critical to note that the methodologies employed in this study may not have fully captured the nuances of numerical cognition in *L. guichenoti*. Therefore, we recommend that future studies employ a broader array of tests and paradigms, including training-based tasks, larger sets of stimuli, and other sensory modalities, to more comprehensively assess numerical competence in this and related species. Such work will be fundamental in unravelling early environmental factors’ effects on reptiles’ cognitive abilities and advancing our understanding of numerical discrimination across taxa.

## Data accessibility

All data, data description, and R code are available in public repository <https://github.com/Pablo-Recio/CORT-Temp_Numerical>.

## Declaration of AI use

We declare Chat GPT was used for questions related to coding and data analyses. All other parts of the manuscript were written by the authors and those parts where AI was used were checked and modified accordingly by the authors.

## Authors’ contributions

PR: conceptualization, methodology, data collection, data curation, formal analysis, writing—original draft, writing—review and editing; DL: data collection, writing—review and editing; OC: conceptualization, writing—review and editing; CF: conceptualization, funding acquisition, writing—review and editing; AP: data collection, writing—review and editing; DN: conceptualization, methodology, funding acquisition, project administration, resources, supervision, writing—review and editing.  
All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

## Conflict of interest declaration

We declare we have no competing interests.

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## References

Abayarathna T, Webb JK (2020) Effects of incubation temperatures on learning abilities of hatchling velvet geckos. Animal Cognition 23:613–620. <https://doi.org/10.1007/s10071-020-01365-4>

Agrillo C, Bisazza A (2014) Spontaneous versus trained numerical abilities. A comparison between the two main tools to study numerical competence in non-human animals. Journal of neuroscience methods 234:82–91

Amiel JJ, Bao S, Shine R (2017) The effects of incubation temperature on the development of the cortical forebrain in a lizard. Animal Cognition 20:117–125. <https://doi.org/10.1007/s10071-016-0993-2>

Amiel JJ, Lindström T, Shine R (2014) Egg incubation effects generate positive correlations between size, speed and learning ability in young lizards. Animal Cognition 17:337–347. <https://doi.org/10.1007/s10071-013-0665-4>

Amiel JJ, Shine R (2012) Hotter nests produce smarter young lizards. Biology Letters 8:372–374. <https://doi.org/10.1098/rsbl.2011.1161>

Bebus SE, Small TW, Jones BC, et al (2016) Associative learning is inversely related to reversal learning and varies with nestling corticosterone exposure. Animal Behaviour 111:251–260. <https://doi.org/10.1016/j.anbehav.2015.10.027>

Beran MJ, Parrish AE (2016) Capuchin monkeys (cebus apella) treat small and large numbers of items similarly during a relative quantity judgment task. Psychonomic bulletin & review 23:1206–1213

Bisazza A, Agrillo C, Lucon-Xiccato T (2014) Extensive training extends numerical abilities of guppies. Animal cognition 17:1413–1419

Bürkner P-C (2017) Brms: An r package for bayesian multilevel models using stan. Journal of statistical software 80:1–28

Cantlon JF, Platt ML, Brannon EM (2009) Beyond the number domain. Trends in cognitive sciences 13:83–91

Carazo P, Font E, Forteza-Behrendt E, Desfilis E (2009) Quantity discrimination in tenebrio molitor: Evidence of numerosity discrimination in an invertebrate? Animal Cognition 12:463–470

Chittka L, Geiger K (1995) Can honey bees count landmarks? Animal Behaviour 49:159–164

Clark BF, Amiel JJ, Shine R, et al (2014) Colour discrimination and associative learning in hatchling lizards incubated at “hot” and “cold” temperatures. Behavioral Ecology and Sociobiology 68:239–247. <https://doi.org/10.1007/s00265-013-1639-x>

Coomber P, Crews D, Gonzalez-Lima F (1997) Independent effects of incubation temperature and gonadal sex on the volume and metabolic capacity of brain nuclei in the leopard gecko (Eublepharis macularius), a lizard with temperature-dependent sex determination. The Journal of Comparative Neurology 380:409–421. <https://doi.org/10.1002/(SICI)1096-9861(19970414)380:3<409::AID-CNE9>3.0.CO;2-6>

Cooper TL, Pardo-Sanchez J, Sosnowski MJ, et al (2024) How to tell more is more: Quantity discrimination in eastern box turtles (emydidae: Terrapene carolina). Journal of Herpetology 58:1–15

Cossin-Sevrin N, Hsu B-Y, Marciau C, et al (2022) Effect of prenatal glucocorticoids and thyroid hormones on developmental plasticity of mitochondrial aerobic metabolism, growth and survival: An experimental test in wild great tits. Journal of Experimental Biology 225:jeb243414

Crino OL, Bonduriansky R, Martin LB, Noble DWA (2023) A conceptual framework for understanding stressinduced physiological and transgenerational effects on population responses to climate change. Evolution Letters

Crino OL, Driscoll SC, Ton R, Breuner CW (2014) Corticosterone exposure during development improves performance on a novel foraging task in zebra finches. Animal Behaviour 91:27–32. <https://doi.org/10.1016/j.anbehav.2014.02.017>

Crino O, Wild KH, Friesen CR, et al (2024) From eggs to adulthood: Sustained effects of early developmental temperature and corticosterone exposure on physiology and body size in an australian lizard

Dayananda B, Webb JK (2017) Incubation under climate warming affects learning ability and survival in hatchling lizards. Biology Letters 13:20170002. <https://doi.org/10.1098/rsbl.2017.0002>

Farrell TM, Neuert MAC, Cui A, MacDougall-Shackleton SA (2015) Developmental stress impairs a female songbird’s behavioural and neural response to a sexually selected signal. Animal Behaviour 102:157–167. <https://doi.org/10.1016/j.anbehav.2015.01.018>

Gazzola A, Vallortigara G, Pellitteri-Rosa D (2018) Continuous and discrete quantity discrimination in tortoises. Biology letters 14:20180649

Haq SU, Bhat UA, Kumar A (2021) Prenatal stress effects on offspring brain and behavior: Mediators, alterations and dysregulated epigenetic mechanisms. Journal of Biosciences 46:34. <https://doi.org/10.1007/s12038-021-00153-7>

Hyde DC (2011) Two systems of non-symbolic numerical cognition. Frontiers in human neuroscience 5:150

Jessop TS, Lane ML, Teasdale L, et al (2016) Multiscale evaluation of thermal dependence in the glucocorticoid response of vertebrates. The American Naturalist 188:342–356

Joss J, Minard J (1985) On the reproductive cycles of lampropholis guichenoti and l. Delicata (squamata: Scincidae) in the sydney region. Australian Journal of Zoology 33:699–704

Lin F-C, Shaner P-JL, Hsieh M-Y, et al (2024) Trained quantity discrimination in the invasive red-eared slider and a comparison with the native stripe-necked turtle. Animal Cognition 27:26

Lin F-C, Whiting MJ, Hsieh M-Y, et al (2021) Superior continuous quantity discrimination in a freshwater turtle. Frontiers in Zoology 18:1–11

Lucon-Xiccato T, Dadda M (2017) Individual guppies differ in quantity discrimination performance across antipredator and foraging contexts. Behavioral Ecology and Sociobiology 71:1–9

Lui E, Salim M, Chahal M, et al (2017) Chronic corticosterone-induced impaired cognitive flexibility is not due to suppressed adult hippocampal neurogenesis. Behavioural brain research 332:90–98

Makowski D, Ben-Shachar MS, Lüdecke D (2019) bayestestR: Describing effects and their uncertainty, existence and significance within the bayesian framework. Journal of Open Source Software 4:1541. <https://doi.org/10.21105/joss.01541>

McComb K, Packer C, Pusey A (1994) Roaring and numerical assessment in contests between groups of female lions, panthera leo. Animal Behaviour 47:379–387

Mentesana L, Hau M (2022) Glucocorticoids in a warming world: Do they help birds to cope with high environmental temperatures? Hormones and Behavior 142:105178

Miletto Petrazzini ME, Bertolucci C, Foà A (2018) Quantity discrimination in trained lizards (podarcis sicula). Frontiers in psychology 9:274

Miletto Petrazzini ME, Fraccaroli I, Gariboldi F, et al (2017) Quantitative abilities in a reptile (podarcis sicula). Biology Letters 13:20160899

Nieder A (2018) Evolution of cognitive and neural solutions enabling numerosity judgements: Lessons from primates and corvids. Philosophical Transactions of the Royal Society B: Biological Sciences 373:20160514

Nieder A (2005) Counting on neurons: The neurobiology of numerical competence. Nature reviews neuroscience 6:177–190

Noble DWA, Stenhouse V, Schwanz LE (2018) Developmental temperatures and phenotypic plasticity in reptiles: A systematic review and meta-analysis: Incubation temperature and plasticity. Biological Reviews 93:72–97. <https://doi.org/10.1111/brv.12333>

Plotnik JM, Brubaker DL, Dale R, et al (2019) Elephants have a nose for quantity. Proceedings of the National Academy of Sciences 116:12566–12571

Qualls FJ, Shine R (2000) Post-hatching environment contributes greatly to phenotypic variation between two populations of the australian garden skink, lampropholis guichenoti. Biological Journal of the Linnean Society 71:315–341

R Core Team (2021) [R: A language and environment for statistical computing](https://www.R-project.org/). R Foundation for Statistical Computing, Vienna, Austria

Racic A, Tylan C, Langkilde T (2020) Effects of temperature on plasma corticosterone in a native lizard. Scientific Reports 10:16315. <https://doi.org/10.1038/s41598-020-73354-z>

Recio P, Rodrı́guez-Ruiz G, López P, Martı́n J (2021) Prey quantity discrimination and social experience affect foraging decisions of rock lizards. Behavioral Ecology and Sociobiology 75:33. <https://doi.org/10.1007/s00265-021-02979-5>

Sapolsky RM, Romero LM, Munck AU (2000) How Do Glucocorticoids Influence Stress Responses? Integrating Permissive, Suppressive, Stimulatory, and Preparative Actions. 21:

Siegel A G. J. (ed) (2006) Basic neurochemistry. Molecular, cellular and medical aspects. Elsevier Academic Press

Soldati F, Burman OH, John EA, et al (2017) Long-term memory of relative reward values. Biology Letters 13:20160853

Stancher G, Rugani R, Regolin L, Vallortigara G (2015) Numerical discrimination by frogs (bombina orientalis). Animal Cognition 18:219–229

Szabo B, Noble DWA, McCloghry KJ, et al (2021) Spontaneous quantity discrimination in a family-living lizard. Behavioral Ecology 32:686–694. <https://doi.org/10.1093/beheco/arab019>

Szuran T, Zimmermann E, Welzl H (1994) Water maze performance and hippocampal weight of prenatally stressed rats. Behavioural Brain Research 65:153–155. <https://doi.org/10.1016/0166-4328(94)90100-7>

Uller C, Jaeger R, Guidry G, Martin C (2003) Salamanders (plethodon cinereus) go for more: Rudiments of number in an amphibian. Animal cognition 6:105–112

Vila Pouca C, Gervais C, Reed J, et al (2019) Quantity discrimination in Port Jackson sharks incubated under elevated temperatures. Behavioral Ecology and Sociobiology 73:93. <https://doi.org/10.1007/s00265-019-2706-8>

Vila Pouca C, Gervais C, Reed J, Brown C (2018) Incubation under Climate Warming Affects Behavioral Lateralisation in Port Jackson Sharks. Symmetry 10:184. <https://doi.org/10.3390/sym10060184>

Vonk J, Beran MJ (2012) Bears ‘count’too: Quantity estimation and comparison in black bears, ursus americanus. Animal behaviour 84:231–238

Zhu Z, Li X, Chen W, et al (2004) Prenatal stress causes gender-dependent neuronal loss and oxidative stress in rat hippocampus. Journal of Neuroscience Research 78:837–844. <https://doi.org/10.1002/jnr.20338>

# Suplementary Material

#### Effects of treatments on numerical discrimination using the estimates and the raw data

*Table S1.- Median and 95% Higest Density Intervals (95% HPDI) of the estimated probability of choosing first the higher amount (Choice) and the estimated interest for the higher amount of food (Interest) per treatment group for each of the numerical tests performed. 95% HPDI test the hypothesis that Choice = 0.5, and Interest = 0, which would indicate a preference towards one of choices.*

|  | | Choice | | Interest | |
| --- | --- | --- | --- | --- | --- |
| Test | Treatment | Median | 95% HPDI | Median | 95% HPDI |
| 1VS4 | Cold-CORT (n = 20) | 0.33 | [0.11 , 0.57] | 8.32 | [-32.46 , 47.59] |
|  |  | 0.47 | [0.24 , 0.73] | -2.57 | [-42.66 , 33.19] |
|  |  | 0.61 | [0.35 , 0.84] | -13.14 | [-53.15 , 26.95] |
|  |  | 0.43 | [0.18 , 0.68] | -4.56 | [-45.31 , 31.48] |
| 1VS3 | Cold-CORT (n = 20) | 0.39 | [0.15 , 0.65] | -19.39 | [-57.92 , 22.15] |
|  |  | 0.65 | [0.4 , 0.86] | -2.63 | [-40.85 , 36.12] |
|  |  | 0.81 | [0.61 , 0.96] | 31.01 | [-5.34 , 72.49] |
|  |  | 0.64 | [0.38 , 0.87] | -8.24 | [-49.16 , 31.37] |
| 2VS4 | Cold-CORT (n = 20) | 0.50 | [0.24 , 0.75] | 12.79 | [-27.26 , 52.63] |
|  |  | 0.48 | [0.24 , 0.72] | -3.54 | [-41.85 , 33.52] |
|  |  | 0.45 | [0.22 , 0.72] | -9.88 | [-48.22 , 29.38] |
|  |  | 0.55 | [0.3 , 0.8] | 8.78 | [-28.76 , 49.13] |
| 2VS3 | Cold-CORT (n = 20) | 0.60 | [0.33 , 0.84] | -9.63 | [-49.88 , 29.68] |
|  |  | 0.76 | [0.55 , 0.94] | 27.68 | [-10.7 , 65.64] |
|  |  | 0.44 | [0.21 , 0.71] | 3.36 | [-37.41 , 42.22] |
|  |  | 0.37 | [0.15 , 0.63] | -28.90 | [-69.87 , 8.26] |
| 3VS4 | Cold-CORT (n = 20) | 0.41 | [0.16 , 0.66] | -30.29 | [-72.03 , 9.21] |
|  |  | 0.59 | [0.34 , 0.82] | 21.85 | [-15.28 , 60.75] |
|  |  | 0.65 | [0.38 , 0.87] | -14.07 | [-56.39 , 25.9] |
|  |  | 0.70 | [0.45 , 0.9] | 14.46 | [-25.34 , 52.95] |

**?(caption)**

*Table S2.- Performance of each treatment in each of the numerical tests using the raw data. For the variable Latency and Interest, we show the median and the 95% CI. For the varaible Choice, we show the proportion of individuals that chose the higher number of crickets first.*

|  | | | | Tests |  | |
| --- | --- | --- | --- | --- | --- | --- |
| Variable | Treatment | 1 VS 4 | 1 VS 3 | 2 VS 4 | 2 VS 3 | 3 VS 4 |
| Latency | Hot-Control (n = 20) | 595.5 [55.88 , 1593.72] | 721.25 [192.5 , 2074.55] | 622.8 [74.23 , 1447.22] | 666.35 [84.63 , 2311.7] | 742.2 [71.33 , 2344.85] |
|  | Hot-CORT (n = 20) | 1235.7 [257.98 , 4483.92] | 1011.5 [203.12 , 2379.73] | 852.4 [115.38 , 2527.57] | 840.9 [98.2 , 2524.95] | 1360.25 [145.43 , 6131.73] |
|  | Cold-Control (n = 20) | 663.35 [84.93 , 2605.7] | 729.95 [92.8 , 3099.77] | 630.5 [94.1 , 2500.82] | 575 [70.75 , 1679.95] | 491.15 [24.63 , 1915.57] |
|  | Cold-CORT (n = 20) | 880.25 [29.75 , 4557.85] | 760.3 [60.08 , 3493.4] | 703 [30.88 , 3522.77] | 962.15 [35.93 , 4747.52] | 1031.05 [19.88 , 4106.82] |
| Choice | Hot-Control (n = 20) | 8 | 12 | 10 | 7 | 13 |
|  | Hot-CORT (n = 20) | 11 | 15 | 9 | 9 | 11 |
|  | Cold-Control (n = 20) | 10 | 13 | 10 | 15 | 12 |
|  | Cold-CORT (n = 20) | 8 | 9 | 11 | 12 | 9 |
| Interest | Hot-Control (n = 20) | -6.5 [-126.97 , 163.07] | -10.68 [-180.9 , 113.25] | 6.6 [-85.05 , 162.3] | -31.1 [-118.62 , 56.62] | 12.05 [-186.6 , 228.85] |
|  | Hot-CORT (n = 20) | -15.11 [-152.65 , 61.45] | 28.65 [-152.27 , 185.65] | -12.74 [-120.8 , 182] | 1.68 [-108.4 , 120.55] | -15.71 [-148 , 84.4] |
|  | Cold-Control (n = 20) | -2.75 [-141.42 , 204.65] | -3.05 [-152.55 , 179.07] | -3.95 [-142.12 , 104] | 27.25 [-77.38 , 130] | 21.55 [-101 , 164.22] |
|  | Cold-CORT (n = 20) | 12.9 [-188.15 , 195.67] | -14.15 [-203.8 , 123.02] | 17.6 [-105.78 , 186.17] | -4.68 [-119.05 , 79.8] | -24.84 [-182.8 , 74.95] |

**?(caption)**

#### Model results

*Table S3A.- Summary of the model fitted for loglatency (Latency)*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_loglatency\_Intercept | 6.47 | 6.47 | 0.31 | 5.96 | 7.00 | 1.00 | 4547.93 | 6871.87 |
| b\_loglatency\_test\_type1VS3 | -0.03 | -0.03 | 0.21 | -0.37 | 0.31 | 1.00 | 5851.20 | 8069.68 |
| b\_loglatency\_test\_type2VS4 | -0.13 | -0.13 | 0.21 | -0.46 | 0.21 | 1.00 | 5607.53 | 8779.16 |
| b\_loglatency\_test\_type2VS3 | -0.02 | -0.02 | 0.21 | -0.36 | 0.33 | 1.00 | 5792.88 | 8099.56 |
| b\_loglatency\_test\_type3VS4 | -0.07 | -0.07 | 0.21 | -0.42 | 0.27 | 1.00 | 5394.76 | 8113.94 |
| b\_loglatency\_tempHot | 0.05 | 0.05 | 0.45 | -0.69 | 0.80 | 1.00 | 4240.55 | 6468.22 |
| b\_loglatency\_cortControl | 0.09 | 0.09 | 0.35 | -0.50 | 0.66 | 1.00 | 3501.90 | 6160.76 |
| b\_loglatency\_sexm | -0.46 | -0.45 | 0.22 | -0.82 | -0.10 | 1.00 | 5456.02 | 7259.40 |
| b\_loglatency\_age | 0.06 | 0.06 | 0.02 | 0.02 | 0.10 | 1.00 | 5242.87 | 6844.75 |
| b\_loglatency\_test\_type1VS3:tempHot | -0.03 | -0.03 | 0.30 | -0.52 | 0.46 | 1.00 | 5246.33 | 7514.61 |
| b\_loglatency\_test\_type2VS4:tempHot | -0.18 | -0.18 | 0.30 | -0.67 | 0.31 | 1.00 | 5432.60 | 8115.85 |
| b\_loglatency\_test\_type2VS3:tempHot | -0.25 | -0.25 | 0.30 | -0.74 | 0.25 | 1.00 | 5517.51 | 7473.31 |
| b\_loglatency\_test\_type3VS4:tempHot | -0.10 | -0.11 | 0.30 | -0.60 | 0.39 | 1.00 | 5247.17 | 7570.16 |
| b\_loglatency\_test\_type1VS3:cortControl | 0.04 | 0.04 | 0.29 | -0.43 | 0.53 | 1.00 | 5376.57 | 7715.18 |
| b\_loglatency\_test\_type2VS4:cortControl | 0.15 | 0.16 | 0.29 | -0.33 | 0.64 | 1.00 | 5492.31 | 8062.19 |
| b\_loglatency\_test\_type2VS3:cortControl | -0.04 | -0.04 | 0.29 | -0.52 | 0.44 | 1.00 | 5459.05 | 7755.73 |
| b\_loglatency\_test\_type3VS4:cortControl | -0.38 | -0.38 | 0.29 | -0.87 | 0.09 | 1.00 | 5264.74 | 8063.37 |
| b\_loglatency\_tempHot:cortControl | -0.78 | -0.78 | 0.49 | -1.58 | 0.03 | 1.00 | 3491.24 | 5908.08 |
| b\_loglatency\_test\_type1VS3:tempHot:cortControl | 0.25 | 0.25 | 0.42 | -0.43 | 0.94 | 1.00 | 5103.28 | 7366.37 |
| b\_loglatency\_test\_type2VS4:tempHot:cortControl | 0.28 | 0.28 | 0.42 | -0.40 | 0.97 | 1.00 | 4860.78 | 7733.09 |
| b\_loglatency\_test\_type2VS3:tempHot:cortControl | 0.37 | 0.37 | 0.42 | -0.32 | 1.05 | 1.00 | 5243.01 | 8532.21 |
| b\_loglatency\_test\_type3VS4:tempHot:cortControl | 0.74 | 0.75 | 0.42 | 0.05 | 1.44 | 1.00 | 5119.54 | 7726.59 |

**?(caption)**

*Table S3B.- Summary of the model fitted for Choice*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_choice\_Intercept | -0.68 | -0.68 | 0.58 | -1.64 | 0.26 | 1.00 | 4717.07 | 6912.29 |
| b\_choice\_test\_type1VS3 | 0.24 | 0.24 | 0.69 | -0.89 | 1.38 | 1.00 | 5106.43 | 7093.98 |
| b\_choice\_test\_type2VS4 | 0.71 | 0.70 | 0.69 | -0.42 | 1.86 | 1.00 | 4984.93 | 7514.81 |
| b\_choice\_test\_type2VS3 | 1.12 | 1.10 | 0.73 | -0.06 | 2.35 | 1.00 | 4902.86 | 6926.45 |
| b\_choice\_test\_type3VS4 | 0.33 | 0.32 | 0.70 | -0.82 | 1.48 | 1.00 | 5219.20 | 7158.11 |
| b\_choice\_tempHot | 1.13 | 1.12 | 0.83 | -0.23 | 2.50 | 1.00 | 4283.18 | 6599.41 |
| b\_choice\_cortControl | 0.61 | 0.60 | 0.74 | -0.59 | 1.84 | 1.00 | 3922.51 | 6114.01 |
| b\_choice\_sexm | -0.06 | -0.06 | 0.30 | -0.54 | 0.43 | 1.00 | 14505.46 | 8697.98 |
| b\_choice\_age | -0.04 | -0.04 | 0.03 | -0.09 | 0.01 | 1.00 | 12392.71 | 8820.47 |
| b\_choice\_test\_type1VS3:tempHot | 0.80 | 0.79 | 1.04 | -0.88 | 2.55 | 1.00 | 4972.18 | 6745.87 |
| b\_choice\_test\_type2VS4:tempHot | -1.33 | -1.33 | 1.00 | -2.98 | 0.29 | 1.00 | 4886.89 | 7191.48 |
| b\_choice\_test\_type2VS3:tempHot | -1.77 | -1.77 | 1.04 | -3.49 | -0.09 | 1.00 | 4289.06 | 6024.53 |
| b\_choice\_test\_type3VS4:tempHot | -0.13 | -0.13 | 1.02 | -1.80 | 1.57 | 1.00 | 4538.82 | 7185.57 |
| b\_choice\_test\_type1VS3:cortControl | 0.48 | 0.47 | 0.99 | -1.15 | 2.12 | 1.00 | 4938.94 | 7818.41 |
| b\_choice\_test\_type2VS4:cortControl | -0.70 | -0.69 | 0.98 | -2.32 | 0.90 | 1.00 | 4749.40 | 7672.85 |
| b\_choice\_test\_type2VS3:cortControl | 0.15 | 0.16 | 1.04 | -1.53 | 1.85 | 1.00 | 4980.80 | 8127.50 |
| b\_choice\_test\_type3VS4:cortControl | 0.14 | 0.13 | 1.00 | -1.50 | 1.77 | 1.00 | 4881.82 | 7388.95 |
| b\_choice\_tempHot:cortControl | -1.33 | -1.32 | 1.06 | -3.06 | 0.40 | 1.00 | 3598.45 | 6418.88 |
| b\_choice\_test\_type1VS3:tempHot:cortControl | -0.65 | -0.64 | 1.44 | -3.01 | 1.71 | 1.00 | 4947.05 | 7258.07 |
| b\_choice\_test\_type2VS4:tempHot:cortControl | 1.82 | 1.79 | 1.41 | -0.52 | 4.12 | 1.00 | 4832.87 | 7213.76 |
| b\_choice\_test\_type2VS3:tempHot:cortControl | 0.25 | 0.25 | 1.45 | -2.12 | 2.59 | 1.00 | 4689.39 | 7011.19 |
| b\_choice\_test\_type3VS4:tempHot:cortControl | 0.81 | 0.80 | 1.44 | -1.57 | 3.20 | 1.00 | 4767.29 | 7038.46 |

**?(caption)**

*Table S3C.- Summary of the model fitted for Interest*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| b\_comparedinterest\_Intercept | 12.58 | 12.75 | 20.03 | -20.62 | 45.52 | 1.00 | 4226.87 | 6914.84 |
| b\_comparedinterest\_test\_type1VS3 | -27.45 | -27.46 | 24.85 | -68.46 | 13.12 | 1.00 | 5057.66 | 7251.20 |
| b\_comparedinterest\_test\_type2VS4 | 4.45 | 4.37 | 25.04 | -36.11 | 45.40 | 1.00 | 4955.22 | 7144.03 |
| b\_comparedinterest\_test\_type2VS3 | -18.02 | -18.08 | 25.03 | -59.03 | 23.55 | 1.00 | 4608.81 | 7655.14 |
| b\_comparedinterest\_test\_type3VS4 | -38.45 | -38.44 | 25.60 | -80.23 | 3.89 | 1.00 | 4974.12 | 7540.36 |
| b\_comparedinterest\_tempHot | -21.42 | -21.25 | 28.74 | -68.59 | 25.65 | 1.00 | 3724.65 | 6038.13 |
| b\_comparedinterest\_cortControl | -10.87 | -10.78 | 25.67 | -53.25 | 31.15 | 1.00 | 3414.61 | 5708.73 |
| b\_comparedinterest\_sexm | -8.60 | -8.64 | 9.32 | -23.92 | 7.03 | 1.00 | 17607.01 | 8664.01 |
| b\_comparedinterest\_age | -0.68 | -0.67 | 0.97 | -2.25 | 0.91 | 1.00 | 15664.51 | 9250.40 |
| b\_comparedinterest\_test\_type1VS3:tempHot | 71.62 | 71.63 | 35.19 | 13.31 | 129.60 | 1.00 | 4600.90 | 6586.40 |
| b\_comparedinterest\_test\_type2VS4:tempHot | -1.40 | -1.38 | 35.97 | -59.74 | 58.37 | 1.00 | 4594.12 | 6529.68 |
| b\_comparedinterest\_test\_type2VS3:tempHot | 34.51 | 34.43 | 35.89 | -23.35 | 93.63 | 1.00 | 4206.05 | 6855.33 |
| b\_comparedinterest\_test\_type3VS4:tempHot | 37.54 | 37.66 | 36.94 | -22.35 | 97.98 | 1.00 | 4702.14 | 7554.35 |
| b\_comparedinterest\_test\_type1VS3:cortControl | 27.46 | 27.64 | 35.35 | -30.54 | 86.37 | 1.00 | 4866.97 | 7599.14 |
| b\_comparedinterest\_test\_type2VS4:cortControl | -5.20 | -5.27 | 35.16 | -62.72 | 52.41 | 1.00 | 4362.77 | 6797.39 |
| b\_comparedinterest\_test\_type2VS3:cortControl | 48.43 | 48.30 | 35.49 | -9.54 | 106.81 | 1.00 | 4047.11 | 6637.73 |
| b\_comparedinterest\_test\_type3VS4:cortControl | 63.11 | 62.88 | 35.72 | 4.22 | 122.72 | 1.00 | 4618.01 | 7533.53 |
| b\_comparedinterest\_tempHot:cortControl | 19.41 | 19.72 | 36.63 | -40.29 | 79.85 | 1.00 | 3346.75 | 5960.45 |
| b\_comparedinterest\_test\_type1VS3:tempHot:cortControl | -75.56 | -75.33 | 50.52 | -157.46 | 7.56 | 1.00 | 4608.18 | 7070.71 |
| b\_comparedinterest\_test\_type2VS4:tempHot:cortControl | 15.19 | 15.16 | 50.30 | -69.06 | 97.00 | 1.00 | 4217.24 | 6394.78 |
| b\_comparedinterest\_test\_type2VS3:tempHot:cortControl | -89.54 | -88.78 | 50.35 | -173.98 | -6.66 | 1.00 | 3896.04 | 6636.15 |
| b\_comparedinterest\_test\_type3VS4:tempHot:cortControl | -43.38 | -43.71 | 51.44 | -127.24 | 41.39 | 1.00 | 4491.70 | 6562.71 |

**?(caption)**

*Table S3D.- Summary of the model fitted for other effects*

| variable | mean | median | sd | q5 | q95 | rhat | ess\_bulk | ess\_tail |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| sd\_clutch\_\_loglatency\_Intercept | 0.34 | 0.34 | 0.19 | 0.04 | 0.67 | 1.01 | 716.16 | 2313.13 |
| sd\_lizard\_id\_\_loglatency\_Intercept | 0.81 | 0.81 | 0.10 | 0.64 | 0.97 | 1.00 | 1725.51 | 2777.99 |
| sd\_clutch\_\_choice\_Intercept | 0.26 | 0.23 | 0.18 | 0.02 | 0.60 | 1.00 | 3913.70 | 5803.67 |
| sd\_lizard\_id\_\_choice\_Intercept | 0.59 | 0.60 | 0.25 | 0.13 | 0.99 | 1.00 | 2047.51 | 3110.77 |
| sd\_clutch\_\_comparedinterest\_Intercept | 9.92 | 9.22 | 6.32 | 1.03 | 21.27 | 1.00 | 4065.36 | 6333.93 |
| sd\_lizard\_id\_\_comparedinterest\_Intercept | 9.31 | 8.34 | 6.38 | 0.81 | 20.85 | 1.00 | 3847.09 | 5748.30 |
| sigma\_loglatency | 0.65 | 0.65 | 0.03 | 0.61 | 0.70 | 1.00 | 12611.43 | 8861.89 |
| sigma\_comparedinterest | 78.78 | 78.70 | 3.03 | 73.99 | 83.90 | 1.00 | 15359.76 | 8383.11 |
| lprior | -29.26 | -29.25 | 0.08 | -29.40 | -29.13 | 1.00 | 8343.29 | 9738.65 |
| lp\_\_ | -3440.63 | -3440.02 | 18.68 | -3472.06 | -3410.58 | 1.00 | 2890.39 | 5974.94 |

**?(caption)**

#### Testing potential side biases

\_Table S4.- Number of individuals per treatment that chose the right (R) or left (L) side in each of the numerical tests. p-value indicates the result of the binomial test comparing the number of choices between sides.

|  | 1 VS 4 | 1 VS 3 | 2 VS 4 | 2 VS 3 | 3 VS 4 |
| --- | --- | --- | --- | --- | --- |
| Control-Cold (n = 20) | R = 12 | L = 8 , p = 0.5 | R = 12 | L = 8 , p = 0.5 | R = 9 | L = 11 , p = 0.82 | R = 12 | L = 8 , p = 0.5 | R = 12 | L = 8 , p = 0.5 |
| Control-Hot (n = 20) | R = 12 | L = 8 , p = 0.5 | R = 5 | L = 15 , p = 0.04 | R = 9 | L = 11 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |
| CORT-Cold (n = 20) | R = 11 | L = 9 , p = 0.82 | R = 11 | L = 9 , p = 0.82 | R = 11 | L = 9 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |
| CORT-Hot (n = 20) | R = 11 | L = 9 , p = 0.82 | R = 9 | L = 11 , p = 0.82 | R = 9 | L = 11 , p = 0.82 | R = 10 | L = 10 , p = 1 | R = 11 | L = 9 , p = 0.82 |

**?(caption)**

#### Prey orientation test

Because the orientation of the crickets could affect the lizards’ choice, we performed one simple choice test to investigate this. We used the same platform and Petri dish as in the numerical discrimination task, but we placed one cricket on each side of the platform, one oriented vertically in respect to the shelter position (see [Fig. 1](#fig-Methods) B) and the other one horizontal to the shelter. We performed a unique trial randomising the position of the orientation of the cricket. We recorded the number of individuals that chose the cricket oriented vertically and horizontally. Results are shown in the table below.

*Table S4.- Number of individuals per treatment that chose the cricket oriented horizontally (Horizontal) or vertically (Vertical) in our control tests. p-value indicates the result of the binomial test comparing the number of choices between both choices.*

|  | Horizontal | Vertical | p-value |
| --- | --- | --- | --- |
| Cold-Control (n = 20) | 8 | 12 | 0.503 |
| Hot-Control (n = 20) | 7 | 13 | 0.263 |
| Cold-CORT (n = 20) | 12 | 8 | 0.503 |
| Hot-CORT (n = 20) | 9 | 11 | 0.824 |

**?(caption)**

#### Searching for relevant literature

To look for relevant literature about the effects of early environment on numerical discrimination, we searched in the Web of Science and Scopus using the terms on respectively. The queries employed are detailed below. We looked for manuscripts for all years available. The last search was conducted on the 11th of October 2024; the results below refer to this last search.

We found 24 articles on Web of Science and 22 on Scopus, plus one preprint on Scopus. Out of all the documents, only one study was relevant to our search: Vila Pouca et al. ([2019](#ref-vila_pouca_quantity_2019)). That study appeared in both databases and was the only one that explored the effects of early environment on numerical abilities.

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| Fig 3— Search query on Web of Science. |

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| Fig 4— Search query on Scopus. |

#### Checking the model plots

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