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From Small to Large: Numerical Discrimination by Young Domestic Chicks (*Gallus gallus*)

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Human adults and nonhuman primates share a subset of nonverbal numerical skills that are considered the evolutionary foundation of more complex numerical reasoning. Intriguing experiments have shown that 10- to 12-month-old infants are able to distinguish between large (8 vs. 12) and small (1 vs. 2, 1 vs. 3, 2 vs. 3) sets of objects but seem incapable of comparing quantities that fall in the middle area between large and small numerosities, such as 1 versus 4. This finding suggests that there are two separate nonverbal numerical systems. Other researchers argue that there is continuity in the representation of numbers. Experimental evidence demonstrating that newborn chicks are able to process addition and subtraction such as (4–1) versus (1 + 1) lends support to the latter hypothesis. Here, using an experimental paradigm to test numerical discrimination, we demonstrated that newborn chicks are able to distinguish between some numerical comparisons, such as 2 vs. 3, 2 vs. 8, 6 vs. 9, 8 vs. 14, 4 vs. 6, and 4 vs. 8. These findings support the hypothesis that a single system processes both small and large numerosities. The results of these experiments demonstrate that small and large numbers can be discriminated via "analogue magnitude" system (AMS). Those data can be accounted for in terms of a select mechanism prompting the functioning of either system and, therefore, a different processing of the stimuli. When the modality of presentation of the stimuli focuses the attention on the whole collection, the elaboration would be carried out by the AMS.

Keywords: number cognition, number discrimination, number sense, visual discrimination learning, domestic chick

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When we think about mathematics, we usually think about a variety of complex calculations that are uniquely human. Those abstract capabilities, linked to words ("three," "five," or "twelve") or symbols referring to numbers ("3," "5," or "12") or calculations ("−", "×") are learned solely by means of an explicit mathematical education (Carey, 2004; Dehaene, 1997; Gallistel & Gelman, 1992; Hauser & Spelke, 2004). We are so accustomed to think about numbers through numerical words that the domain of numerical competences has been considered a prerogative of acculturated adults. Humans can, nevertheless, still perform some calculations without the help of language. This nonverbal number sense can be found, for example, in tasks requiring individuals to add two sets of dots presented sequentially and then to choose between a correct or an incorrect alternative. The finding that college students and rhesus monkeys (*Macaca mulatta*) share a core set of abilities for comparing approximate numerosities nonverbally is considered the best evidence that humans share a numerical processing mechanism with other animal species (Cantlon & Brannon, 2007).

Although this is the most direct evidence of an ancestral numerical mechanism shared by humans and nonhumans, other supporting data has been obtained from studies on nonhuman creatures (reviews in Haun, Jordan, Vallortigara, & Clayton, 2010; Vallortigara, Chiandetti, Sovrano, Rugani, & Regolin, 2010). Findings based on experiments carried out in a variety of species suggest that nonverbal mathematical reasoning is based on two systems. Small, precise calculations can be explained in terms of an object file hypothesis, according to which each object presented in a visual scene is represented by a unique symbol called an "object file" that is stored in a working memory. This system works by tracking spatiotemporal information, property/kind changes, and object features such as color, size, and shape to identify each new object that is introduced into a scene. Although the system is not specific to a number representation, numbers are implicitly repre-

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sented. Because the “object file system” (OFS) can simultaneously represent a limited number of indexes, as a consequence it can track only small numbers, up to 3 or 4 individual objects (Trick & Pylyshyn, 1994). Differences at the upper limit, 3 in the case of salamanders (*Plethodon cinereus*; Uller, Jaeger, Guidry, & Martin, 2003) fishes (*Xenotoca eiseni*; Stancher, Sovrano, Potrich, & Vallortigara, 2013), chicks (*Gallus gallus*; Rugani, Regolin, & Vallortigara, 2008) and 4 in the case of adult monkeys (*Macaca mulatta*; Hauser, Carey, & Hauser, 2000), have been attributed to maturational factors (Carey, 2009).

Estimations involving approximate numerosities or analog magnitudes are referred to as the AMS, and its functioning can be classified by two effects. The *Numerical Distance Effect* is when discrimination becomes easier as the relative magnitude of the values being compared becomes numerically more distant (i.e., it is simpler to discriminate between 8 vs. 30 than between 8 vs. 10). The *Numerical Size Effect* occurs when the numerical disparity is constant, and it is easier to discriminate between smaller values (i.e., it is simpler to discriminate between 8 vs. 10 than 80 vs. 82). As a result and in accordance with the Weber’s Law, the capacity to discriminate between two quantities becomes increasingly accurate as the ratio approaches 1 (Gallistel & Gelman, 1992).

What is unquestionable is that the OFS operates in relation to small numbers (Trick & Pylyshyn, 1994) and the AMS in relation to larger ones (Gallistel & Gelman, 1992). Contrasting evidence has been produced indicating that the AMS is also linked to discrimination even with regard to small sets of numbers (Brannon & Terrace, 1998; Cantlon & Brannon, 2007; Pepperberg, 2012; Rugani, Vallortigara, & Regolin, 2013), while other data seem to suggest that these are processed only via OFS (Feigenson & Carey, 2005). It has been seen that 10- to 12-month-old infants select the larger quantity of crackers when they are encouraged to choose between 1 vs. 2, 1 vs. 3, 2 vs. 3, but not between 1 vs. 4 (Feigenson, Carey, & Hauser, 2002). This confirms that they are able to distinguish between quantities, such as 2 and 3 (ratio = 0.667) separated by a single element, but not between those spaced further apart (1 and 4). Intriguingly, infants that same age are able to discriminate between comparisons characterized by the same ratio but involving larger numbers: 8 vs. 16 (ratio = 0.5) and 8 vs. 12 (ratio = 0.667; Feigenson, Dehaene, & Spelke, 2004). Taken together, these data seem to suggest that there are two separate, independent systems that account for nonverbal representations of numbers: one concerning small values (<3) thought to be incapable of processing larger ones and another one for large magnitudes (>4) thought to be incapable of processing small values (see the lack of discrimination in the comparison 1 vs. 4).

Evidence supporting continuity in processing small and large numbers in humans and nonhumans has also been described. When adults are unable to use numerical words, in fact, they seem to rely on AMS to distinguish both small and large numbers (Cordes, Gelman, Gallistel, & Whalen, 2001). Using a manual bisection paradigm, de Hevia and Spelke (2009) showed preschool (5-year-old) and school (7-year-old) children systematically distorted localization of the midpoint of a horizontal line when a small and a large numerousness (e.g., 2 vs. 9) of dots were located at the extremities of the line. Employing a habituation–dishabituation task, Cordes and Brannon (2009) demonstrated 7-month-old infants discriminating between a small and a large set of elements (e.g., 2 vs. 8). Chimpanzees (*Pan troglodytes*) discriminated between two sets each comprising a different number of sequentially presented food items (e.g., 2 vs. 4, 2 vs. 5, 3 vs. 5, and 4 vs. 6) to reach the larger amount of food (Beran, 2001). Chimpanzees (*Pan troglodytes*), gorillas (*Gorilla gorilla*), bonobos (*Pan paniscus*), and orangutans (*Pongo pygmaeus*) compared two sets, each containing a different number (within the range of 1–6) of cereal bits and chose the larger quantity when these were presented simultaneously or sequentially (Hanus & Call, 2007). Rhesus monkeys (*Macaca mulatta*) selected the larger of two sequentially presented sets of items also when a set had fewer than 4 items and the other more than 4 items (Beran, 2007). After being trained to place 1 to 4 elements in ascending order, monkeys were able to utilize that knowledge when they were tested with regard to numbers from 5 to 9 (*Macaca mulatta*: Brannon & Terrace, 1998; Cantlon & Brannon, 2007; *Papio hamadryas* and *Saimiri sciureus*: Smith, Piel, & Candland, 2003; and *Cebus apella*: Judge, Evans, & Vyas, 2005). Bottlenose dolphins (*Tursiops truncatus*) trained to select the set with the fewer number of items employing a few specific comparisons (e.g., 1 vs. 3, 2 vs. 6, and 3 vs. 7) were able to generalize to all possible pairwise comparisons between 1 and 8 (Jaakkola, Fellner, Erb, Rodriguez, & Guarino, 2005). Domestic dogs (*Canis lupus familiaris*) selected the larger amount of hotdog, in the comparisons 1 vs. 2, 1 vs. 3, 1 vs. 4, 2 vs. 3, 2 vs. 4, 2 vs. 5, 3 vs. 4, and 3 vs. 5 (Ward & Smuts, 2007). Asian Elephants (*Elephas maximus*, when simultaneously presented with two baskets, each containing different numbers of pieces of fruit, identified divergences of quantities up to 6 (4 vs. 1, 3 vs. 1, 4 vs. 2, 5 vs. 3, 2 vs. 1, 3 vs. 2, 4 vs. 3, 5 vs. 4, and 6 vs. 5) without showing disparity or magnitude effects (Irie-Sugimoto, Kobayashi, Sato, & Hasegawa, 2009). Similar findings have been reported with reference to avian species. An African gray parrot (*Psittacus erithacus*) was, for example, able to treat numbers in a continuative way and to use labels when it was made to order numbers from 1 to 8 (Pepperberg, 2012). Robins (*Petroica longipes*), instead, are capable of selecting the larger of two quantities when they are presented with two sets of food items such as 6 vs. 8, 8 vs. 64, and 16 vs. 64 (Garland, Low, & Burns, 2012). It has also been found that newborn domestic chicks can perform a series of addition and subtraction operations/comparisons such as “(**4**−*1*) versus (**1**+*1*)”, “(**5**−*2*) versus (**0**+*2*)”, “(**4**−*2*) versus (**1**+*2*)”, and “(**5**−*3*) versus (**0**+*3*). During the first series of elements-presentations (shown in **boldface**), the task required to calculate a certain number of elements (up to 4 or 5) within a single set and a small number (0, 1, 2, or 3) within another one. During a subsequent series of elements-presentation (in *italics*), one or more elements was/were moved from behind one screen to behind another one. During a first part of elements-presentation, the chicks (*Gallus gallus*) had to calculate an “intermediate” (4) or a “large” (5) number of elements within a single set and a small number (0, 1, 2, or 3) within another. In a subsequent series of elements-presentation, chicks had to update the representation of the two sets to finally discriminate 2 vs. 3 elements (Rugani, Fontanari, Simoni, Regolin, & Vallortigara, 2009).

Hyde and Spelke (2011) recently suggested that the way stimuli are presented can trigger the selective functioning of the OFS or the AMS. According to that hypothesis, the simultaneous presentation of whole sets of elements directs attention to the entire collection, thus activating AMS processing. On the contrary, presenting the elements one after another focuses attention on each object, thus activating the OFS processing, which concentrates on single objects at the expenses of the overall set and which in any case cannot contain more than three elements. This theory should suggest that a different discrimination could be related to the modality of stimuli presentation. For this reason, in the present series of experiments, we designed experiments in which identical objects were presented simultaneously to newborn chicks. We hypothesized that this type of presentation would direct attention toward the whole pattern of elements being presented and elicit processing by AMS. The chicks (*Gallus gallus*) being studied learned that food was located in close proximity to one stimulus and not to another. This was done to test the chicks' ability to discriminate between the two stimuli differing in numerousness. That procedure had already been utilized to test chicks' ability to discriminate between possible and impossible objects (Regolin, Rugani, Stancher, & Vallortigara, 2011) and chicks' sensitivity of the Ebbinghaus illusion (Rosa Salva, Rugani, Cavazzana, Regolin, & Vallortigara, 2013).

In the present work, we conducted a series of experiments in which newly hatched domestic chicks (*Gallus gallus*) were tested in a numerical discrimination task. To understand whether a continuity would be there in processing small, boundary, and large numbers, different numerical comparisons were employed. In Experiment 1, discrimination of small (2 vs. 3), large (6 vs. 9, 8 vs. 12), and boundary (2 vs. 8) sets were compared. In Experiment 2, we tested for the possibility of chicks to discriminate between large sets (8 vs. 14) when continuous variables (area, perimeter) were controlled for. In Experiment 3, the discrimination between the intermediate value (4) from a large value (6 or 8) has been tested in a condition in which both quantitative and numerical cues were available. In Experiment 4, the capability to distinguish an intermediate value (4) from a large one (8) has been tested, controlling for the possible use of quantitative variables (area or perimeter).

Experiment 1

The goal of the first experiment was to investigate the chicks' ability to discriminate between small, large, and cross-boundary numerosities.

Chicks (*Gallus gallus*) are able to distinguish between small sets of elements (1 vs. 2 and 2 vs. 3) even when continuous physical variables are being controlled (Rugani et al, 2008, 2010), but data concerning large numerosities are contrasting. Chicks trained to peck one of two cardboard stimuli, each depicting a certain number of identical elements, failed to discriminate when intermediate (i.e., 4) and large (5 or 6) numerosities were used (i.e., in comparisons 4 vs. 5 and 4 vs. 6; Rugani et al., 2008). When chicks underwent a test in which different numbers of artificial imprinting objects were made to disappear behind one of two identical screens, it was found that they discriminated between larger numerousness: 5 vs. 10 and 6 vs. 9 (Rugani, Regolin, & Vallortigara, 2011). This behavior could, however, have been conditioned by the experimental paradigms employed. The chicks failed to discriminate between large numbers when the task required that they respond by pecking on the stimuli. Because pecking is a grasping action, this may cause attention to be directed toward the details of a single stimuli rather than on the whole configuration, inducing the chick to disregard the overall numerosity of the elements (Rugani et al., 2008).

The chicks studied here were not trained by operant conditioning, nor were they required to respond by pecking on the stimuli. They were simply exposed for approximately 2 days to a situation in which food was located behind a group of stimuli representing a certain numerosity. They were then left to freely choose between the two stimuli, differing in numerosity, and we expected them to preferentially move toward the numerosity that had been incidentally associated with the food. Chicks were given a choice among exclusively small sets (2 vs. 3), exclusively large sets (6 vs. 9 and 8 vs. 12), and sets that lie on different sides of the set size boundary (2 vs. 8). Our aim was to ascertain whether there was continuity in the processing that the newborn chicks used with reference to small and large numbers, as has already been demonstrated in adults (Cordes et al., 2001), children (de Hevia & Spelke, 2009), human infants (Cordes & Brannon, 2009), and other species (*Macaca mulatta*: Cantlon & Brannon, 2007; Brannon & Terrace, 1998; *Papio hamadryas* and *Saimiri sciureus*: Smith et al., 2003; *Cebus apella*: Judge et al., 2005; *Psittacus erithacus*: Pepperberg, 2012).

Method

Ethics statement. The experiments with chicks complied with all national laws and were approved by the Minister of Health (permit number: 5/2012, which was emitted on October 1, 2012).

Subjects. One hundred ninety "Hybro" domestic chicks (*Gallus gallus*), a local variety of the White Leghorn breed, were studied. They were obtained weekly, every Monday morning when they were a few hours old from a local commercial hatchery (Agricola Berica, Montegalda, Vicenza, Italy). On arrival, the chicks were housed individually in standard metal cages (28 × 32 × 40 cm). The rearing room was kept under constant control for temperature (28–31 °C) and humidity (68%) and constantly illuminated by fluorescent lamps (36 W) located 45 cm above each cage. Water was available ad libitum during overall the rearing period, and it was placed in transparent glass jars (5 cm in diameter, 5 cm high) in the center of each cage. During the first 3 days, considered the rearing period (from Monday to Wednesday morning), the chicks could find food behind two of the four vertical plastic screens (10 × 14 cm) located approximately 10 cm in front of the cage's 4 corners. The two screens hiding food were decorated in the same identical way, while the other two screens not associated with food were decorated in a different way. All of the screens were covered with static 2D images representing a given number of elements (each element was a black square whose side length was 1 cm) printed on identical white rectangular plastic boards (11.5 × 9 cm). The screens hiding food (*positive stimuli*, S^{p}) differed from those hiding empty jars (*neutral stimuli*, S^{n}) in the number of elements depicted on them. The following numerosities were used: two (2ES: two elements), three (3ES), six (6ES), eight (8ES), nine (9ES), and 12 (12ES). Three numerical comparisons were employed: 2 vs. 3 ($N = 29$, of which 2ES [S-^{p}] $N = 15$, and 3ES [S-^{p}] $N = 14$); 6 vs. 9 ($N = 57$, of which 6ES [S-^{p}] $N = 27$, and 9ES [S-^{p}] $N = 30$; 8 vs. 12 ($N = 60$, of which 8ES [S-^{p}] $N = 30$, and 12ES [S^{p}], $N = 30$); and 2 vs. 8 ($N = 44$, of which 2ES [S-^{p}] $N = 25$, and 8ES [S^{p}], $N = 19$). During the 3-day preliminary period there were four screens: two representing S-^{p}

and two representing S^n; moreover, for each comparison, half the subjects had a Fewer Numerosity Stimulus as S-^{p}, and the other half had a Larger Numerosity as S^p. To prevent the chicks from learning to identify the stimuli on the basis of the spatial disposition of the elements on the boards, six different pairs of stimuli were used. In each, the elements' disposition on the screen was randomly determined so that the distance between elements varied from 0.3 to 3.8 cm. Three times during the rearing period, the stimuli were replaced, so that each chick was exposed, for about 8 hr, to each pair of stimuli. Every time the stimuli was changed, the location of the S^p and S^n at the corners of the cage was also rotated in order to avoid positional learning.

Each group of chicks underwent testing to verify how the rearing period affected their numerical discrimination. Testing stimuli and numerosities used were the same as those present during the rearing period but the elements were presented in a different spatial disposition.

Apparatus and procedure. Testing took place in an experimental room, adjacent to the rearing room, in which temperature and humidity were controlled (25 °C and 70%, respectively) and which was kept dark except for light coming from two lamps (40 W) placed 25 cm above either end of the apparatus. This (Figure 1) consisted of a runway (45 cm long, 20 cm wide, and 30 cm high). One of the stimuli was placed at each end of the apparatus, at a height of 2 cm, so that it was wholly visible to a chick placed in the central area of the apparatus. The positions of the two testing stimuli and the bird's starting position (i.e., with a stimulus either to the left or to the right) were balanced across individuals. Food reinforcement was not located in proximity of the S^p nor in proximity of the S^n, therefore, odors could not affect chicks' choice. The apparatus was divided into three compartments (each 15 cm long): a central, starting area considered a no-choice zone, and two side compartments (choice areas), which were each considered indicative of a preference for the stimulus located on that side. At the beginning of the experiment, the chick was placed in the starting position and its behavior was filmed throughout its duration, that is, 6 min. Placed above the apparatus and connected to a monitor, the video camera enabled the experimenter to track the chicks' behavior during the test without being seen using a computer-operated device. This was activated every time a chick entered a choice area and registered the amount of time each chick spent near to either stimulus.

An index of choice was calculated for every chick according to the formula used to analyze choice behavior (Andrew, 1991):

Times spent near to the S^p/(Time spent by S^n + Time spent by S^p) were calculated. Values not statistically different from 0.5 indicated no preference for either stimulus; values statistically above 0.5 indicated a preference for S^p and values statistically below 0.5 indicated a preference for S^n. Significant differences with respect to chance levels (0.5) were calculated by one-sample two-tailed t tests.

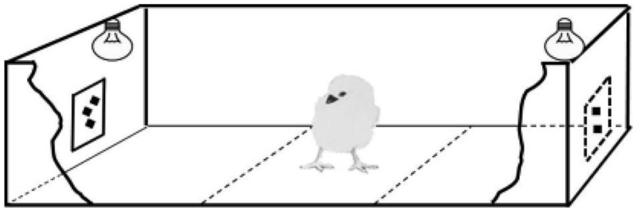

Figure 1. The apparatus used in all of the experiments.

Results and Discussion

An analysis of variance (ANOVA), with comparison (2 vs. 3, 2 vs. 8, 6 vs. 9, and 8 vs. 12) and S^p (the fewer vs. larger numerousness stimulus) as independent variables, was run. The dependent variable was the index of choice for S^p. The interaction of Comparison × S^p, $F(3, 182) = 0.463$; $p = .709$; the main effect of S^p, $F(1, 182) = 0{,}074$; $p = .786$; and the main effect of comparison, $F(3, 182) = 1.554$; $p = .202$; 2 vs. 3: $N = 29$, $M = 0.623$, 95% confidence interval [CI] = 0.473, 0.772; 6 vs. 9: $N = 57$, $M = 0.593$, 95% CI = 0.511, 0.675; 8 vs. 12: $N = 60$, $M = 0.532$, 95% CI = 0.464, 0.600; 2 vs. 8: $N = 44$, $M = 0.602$, 95% CI = 0.535, 0.669) were not significant. The data were merged together and the index of choice of the overall group (Figure 2) was found to be significantly above chance level ($N = 190$, $M = 0.580$, 95% CI = 0.548, 0.612); $t(189) = 5.000$; $p < .001$, effect size: $r = .880$.

Results of this experiment demonstrated that chicks can discriminate between two small (2 vs. 3) and between two large (6 vs. 9) numerical values. It is possible that chicks used the OFS to discriminate the small values and the AMS to discriminate the large ones. Nevertheless, chicks' capability to distinguish between a small and a large value (2 vs. 8) supports the continuity hypothesis, proving that the AMS can represent small values, at least when these are compared with a large one. Processing by AMS could also be expected as a result of the paradigm employed during the experiment. The simultaneous presentation of the elements would point to the same conclusion (Cordes & Brannon, 2008, 2009). Seven-month-old infants are able to discriminate between a small and a large set of elements (2 vs. 8): infants, habituated to arrays containing 2 or 8 dots, at test looked longer at the novel numerousness (Cordes & Brannon, 2008, 2009). Different evidence has been found employing a different paradigm. Ten- to 12-months-old infants were sequentially presented with two quantities of cereals: initially, the first quantity was presented and then made to drop in one opaque container; thereafter, the same happened for the second quantity. When allowed to make a choice, infants selected the larger quantity when choosing between two small or two large numbers, but they performed at chance when one set was small and the other was large in the 2 vs. 8 comparison (vanMarle, 2013). Diverse results could be because of different factors such as the modality of presentation of the stimuli, the duration of exposure, and the paradigm employed.

Experiment 2

Experiment 1 showed that chicks could discriminate between two small and between two large numbers. It is interesting that they can distinguish also between a small and a large number, suggesting that there is continuity in processing numbers along the numerical continuum. But because the stimuli were not controlled for continuous physical variables (e.g., area, contour length), it is unclear whether those discriminations were based on numerical or quantitative cues. With regard to small numerousness, previous works have demonstrated that chicks rely on numbers rather than

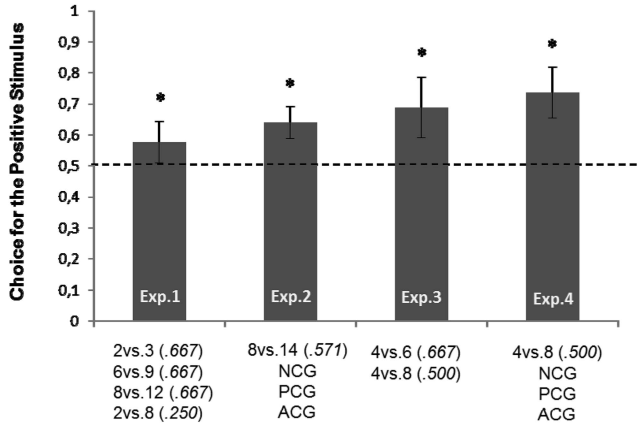

Figure 2. Choice (means with confidence interval [CI]) displayed at test by the chicks, expressed as preference stimulus associated with food. NCG is the acronym of "No Control Group," PCG of the "Perimeter Control Group," and ACG of the "Area Control Group."

on other quantitative variables. Comparable data were obtained by utilizing different paradigms. After being trained to discriminate small sets of identical elements, chicks were then tested to see how they would choose (unrewarded) when they were presented with numerousness, identical to the ones experienced during rearing, whose physical variables such as spatial distribution, contour length, and overall surface were equalized between the two testing stimuli. In all, the conditions when the quantitative variables were simultaneously controlled, the chicks continued to discriminate 1 vs. 2 and 2 vs. 3 (Rugani et al., 2008). In another study, newly hatched domestic chicks were reared with a group of identical objects. When the chicks were 4 days old, they underwent free choice tests in which sets of two and three objects were presented individually and made to disappear (one object at a time) behind one of two identical opaque screens. The chicks spontaneously inspected the screen occluding the larger set even when total surface area and contour length were being controlled (Rugani et al., 2009).

Because numerical discrimination of small sets of elements has already been demonstrated, we intended to focus here on large numbers in the attempt to comprehend whether these are discriminated solely on the basis of numerical cues when continuous physical variables (area and perimeter) were being controlled. In this experiment, we utilized a (8 vs. 14) comparison with a .571 ratio, which is easier to discriminate than the one used in the Experiment 1 (.667).

Method

A new group of 84 chicks was used. The rearing conditions were the same as those described in the previous experiment. For one subgroup of chicks (group-8ES, $N = 49$), S^p represented 8 elements (8ES) and for the second (group-14ES, $N = 43$), S^p represented 14 elements (14ES). Six pairs of rearing stimuli were used, differing from one other with regard to the spatial disposition of the elements (black squares whose side length was 1 cm).

Testing stimuli were composed of elements (black squares) placed in a different way with respect to each rearing ones. Three testing conditions were compared, using varying dimensions of stimuli in each. In the No Control Group (NCG; $N = 31$, with group-8ES $= 15$ and group-14ES $= 16$), the dimensions of the elements, in both the 8ES and the 14ES, were kept identical to those in the rearing situation (squares whose side length was 1 cm long). In the Perimeter Control Group (PCG; $N = 18$, with group-8ES $= 9$, and group-14ES $= 9$), the overall perimeter of the two stimuli was equated. This was obtained in the case of the 8ES group with squares having a side length 1.1 cm long and for the 14ES group a side length 0.6 cm long. In the Area Control Group (ACG; $N = 35$ with group-8ES, $N = 17$ and group-14ES, $N = 18$), the overall areas of the two stimuli were equated (with squares for the 4ES having a side length 1 cm long and those for the 8ES having a side length 0.75 cm long).

Results and Discussion

An ANOVA with S^p (8ES or 14ES) and testing condition (NCG, PCG, or ACG) as between-subjects variables was run. The dependent variable was the index of choice for S^p. The ANOVA did not uncover a significant main effect for S^p, $F(1, 78) = 0.286$, $p = .594$; 8G: $N = 42$; $M = 0.631$, 95% CI = 0.560, 0.712; 14G: $N = 42$; $M = 0.647$, 95% CI = 0.568, 0.726, or for testing condition, $F(2, 78) = 1.039$; $p = .359$: NCG: $N = 31$; $M = 0.671$, 95% CI = 0.593, 0.749; PCG: $N = 18$; $M = 0.666$, 95% CI = 0.516, 0.816; ACG: $N = 35$; $M = 0.597$, 95% CI = 0.522, 0.672. Data were therefore merged and the resulting mean ($N = 84$; $M = 0.639$, 95% CI = 0.587, 0.6691; Figure 2) was found to be significantly above chance levels, one-sample t test, $t(83) = 5.346$; $p < .001$, effect size: $r = .884$. The interaction (Testing Condition × Positive Stimulus) was not significant, $F(2, 78) = 0.003$, $p = .952$.

These results demonstrate that chicks discriminate between large numbers of elements even when quantitative variables (area and perimeter) are being controlled.

Experiment 3

The previous experiments showed that the chicks were able to discriminate when numerousness being compared were both small (2 vs. 3), small and large (2 vs. 8), and both large (6 vs. 9 and 8 vs. 14). Because large numbers (i.e., 8) can be treated solely by the AMS, and considering the success in distinguishing a large number from a small one (2 vs. 8), small and large numerical values could have been processed by the same system: the AMS. If that is the case, discriminations should theoretically be solved involving an in-between value (4; the one that is at the edge of the two numerical systems, an experimental demonstration of the localization of this value in the numerical continuum is reported in Rugani, Cavazzana, Vallortigara, & Regolin, 2013; Rugani et al., 2008, 2010). Discriminations involving the intermediate value (4) and a large one (6 or 8) were thus utilized in the next experiment.

Method

A new group of 70 chicks was utilized. Rearing conditions were exactly the same as those described for the previous experiments. Stimuli representing different numbers (four, 4ES; six, 6ES; and eight, 8ES) of elements (black squares whose side length was 1 cm) were used. Two numerical comparisons 4 vs. 6 ($N = 30$, with group-4ES, $N = 15$; and group-6ES, $N = 15$) and 4 vs. 8 ($N = 40$, with group-4ES, $N = 20$ and group-8ES $N = 20$) were considered. For both comparisons, six different pairs of rearing stimuli whose elements were randomly positioned (the distance between the elements range from 0.3 to 3.7 cm within a window of 11 × 8.5 cm) were used. Testing stimuli consisted of two new sets of black squares that had the same identical dimensions as those used during the rearing period.

Results and Discussion

A *t* test comparing the index of choice registered by the two groups did not reveal any significant difference, $t(68) = 0.067$; $p = .614$; 4 vs. 6: $N = 30$; $M = 0.671$, 95% CI = 0.546, 0.796; 4 vs. 8: $N = 40$; $M = 0.705$, 95% CI = 0.632, 0.779). Data from the two groups were therefore merged, and the resulting mean ($N = 70$; $M = 0.688$, 95% CI = 0.590, 0.786; Figure 2) was found to differ from chance levels, one-sample *t* test, $t(69) = 3.837$; $p <$ .001, effect size: $r = .764$.

These data showed that chicks are able to discriminate between two sets of elements characterized by different ratios 0.5 (4 vs. 8) and 0.667 (4 vs. 6) and including the value of 4, supporting evidence reported in the developmental literature. Seven-month-old infants have been shown able to distinguish 1 vs. 4 and 2 vs. 8 (Cordes & Brannon, 2009). Moreover vanMarle and Wynn (2009) demonstrated that 7-month-old infants could discriminate 2 from 4 tones (a 0.5 ratio), but failed to discriminate 2 from 3 tones (a 0.667 ratio). This ratio-dependent discrimination is the same as that found for infants' discrimination of large numbers (vanMarle & Wynn, 2006), suggesting that infants represent also small numbers via AMS (vanMarle & Wynn, 2009).

Experiment 4

Experiment 3 showed as chicks could discriminate between an intermediate value (4) and a large one (6 or 8), when both quantitative and numerical cues were available. The aim of this experiment was to evaluate whether a comparison utilizing an intermediate value (4) can be discriminated from a large one solely on the basis of numerical cues when quantitative variables (area and perimeter) are being controlled during testing. Because there was no difference in the comparisons tested in Experiment 3, we arbitrarily decided to compare a set of 4 elements with one of 8 elements.

Method

A new group of 56 chicks was utilized. Rearing conditions were exactly the same as described in the previous experiments. All chicks were tested using the same numerical comparison: 4 vs. 8. Rearing stimuli consisted of six pairs each of 4 and 8 black squares whose side length was 1 cm long; therefore, both numerical and quantitative cues were available in this experimental phase. Testing stimuli consisted once again of black squares but with a different spatial disposition and size, with respect to the rearing stimuli and that varied in the two testing conditions. Size variation of testing stimuli allowed controlling for area and perimeter in two different groups of chicks. In the PCG ($N = 27$, with group-8ES, $N = 13$, and group-4ES, $N = 14$) the overall perimeters of the two stimuli were equated. The squares of the 4ES had side lengths 1.5 cm long and the squares of the 8ES had a side length 0.75 cm long. In the ACG, ($N = 29$, with 8G = 14, and 4G = 8), the overall areas of the two stimuli were equated (the 4ES had squares whose sides lengths were 1.5 cm long, and the 8ES had squares whose sides lengths were 1.05 cm long).

Results and Discussion

The *t* test, comparing the index of choice registered by the two groups did not reveal any significant differences, $t(54) = 1.139$; $p = .260$: PCG: $N = 29$; $M = 0.703$, 95% CI = 0.621, 0.785; ACG: $N = 27$; $M = 0.769$, 95% CI = 0.683, 0.855). Data were therefore merged, and the resulting mean ($N = 56$; $M = 0.736$, 95% CI = 0.654, 0.818; Figure 2) was found to be significantly above chance levels, one-sample *t* test, $t(55) = 5.756$; $p < .001$, effect size: $r = .861$.

These data show that chicks can master discriminations involving an intermediate (4) and large value (8) even when the quantitative variables (area or perimeter) are being controlled. This seems to support the idea that chicks' AMS can process the full number range, from small to large, along a numerical continuum. Nevertheless, it should be considered the fact that in the critical 2 vs. 8 cross boundary comparison (Experiment 1), stimuli were not controlled for the possible use of quantitative variables. Whether chicks discriminate on the basis of number or on the basis of quantitative variables in this case is still an open issue.

General Discussion

The aim of this study was to investigate the different processing mechanisms of numerosities pertaining to the OFS and the AMS. Although there is no reason to expect small numbers to be treated differently from large ones, this dissociation does at times occur. It is difficult to interpret the data found in the literature, as the processing mechanisms underlying numerical representations are poorly understood. A recent work using event related potentials demonstrated that the modality of stimulus presentation can produce diversified patterns of brain response activation. A new explanation hypothesizing two core systems underlying numerical cognition has been proposed on the basis of those data (Hyde & Spelke, 2011). According to that hypothesis, these systems do not seem to be specialized for processing small or large numbers. Instead, an attentional selection would activate an analysis of the stimuli by the AMS or the OFS. When the modality of stimulus presentation focuses on the distinct identity of the elements, the OFS does the processing. When, instead, attention is directed to the whole collection, the elaboration is processed by the AMS (Hyde & Spelke, 2011). Data gathered during the experiments outlined here are consistent with this theory.

Four experiments investigating numerical discrimination in newborn chicks have been described. In particular we focused on the chick's capacity to compare small and large numbers by AMS. To avoid processing of the stimuli by the OFS, we used quantities too large (>4) to be handled by that system. Moreover, simultaneous presentation of the stimuli directed attention not on each element (by OFS), but on the overall collection (by AMS). When presented with small numbers of elements one at a time, infants concentrate their attention on each of these, elaborating each as an individual through object-based attention. From these one-by-one representation of individual identities, their numerical estimates can be inferred. When, instead, elements are presented all at the same time, as in our experiment, the whole collection of elements seems to be represented. In Experiment 1, chicks' capability to distinguish between a small and a large number is showed by the success in discrimination 2 vs. 8. In fact, even if the stimuli presentation should trigger for an elaboration supported by the AMS, chicks may have represented small sets (2 vs. 3) exclusively with the OFS and large ones (6 vs. 9) with the AMS. Nevertheless data on the 2 vs. 8 comparison confirmed that animals can rely on the same cognitive system (the AMS) to distinguish quantities along the numerical continuum. Experiment 2 extends the findings from the first one by controlling physical variables and shows that chicks discriminate small and large comparisons, reacting to numbers and not to quantitative perceptual variables. Experiment 3 showed that *AMS* can process discriminations involving an intermediate (4) and large value (6 or 8). Finally, Experiment 4 demonstrated that discrimination between large numbers can be based only on numerical cues when quantitative variables are being controlled.

Overall, these findings lead to two hypotheses. The numerical systems can interact in some way: for example, chicks may have initially represented small sets exclusively with the *OFS* and large sets with the AMS, and therefore converted the OFS representation into an AMS representation, before discrimination occurred. Alternatively the AMS can take charge of discriminations throughout the numerical continuum, without any involvement of the OFS. The data gathered here and using other experimental procedures favoring overall processing of both types of stimuli have led us to sustain the latter one.

Differences between present findings and previous data in this species are apparent. When birds are trained to peck, for food reinforcement on a card representing a certain number of identical elements, they can distinguish 1vs. 2, 2 vs. 3, but not 4 vs. 6. This has been interpreted as an indication that the OFS not the AMS is at work in this species (Rugani et al., 2008). Nevertheless, further data, such as those being presented here, demonstrated the AMS is available at an early age in domestic chicks when different stimuli and paradigms are employed. The lack of discrimination in Rugani et al. (2008) should therefore be interpreted considering the behavioral response (i.e., pecking) that animals were trained to emit in order to indicate a choice. Because pecking can be considered a grasping action, subjects are likely to focus their attention on one or few of the elements presented in the stimuli, rather than on the overall collection. This would cause an activation of the system specialized for representing objects (i.e., the OFS) and causing the lack of discrimination for sets larger than 2 vs. 3.

In a recent study, employing the spontaneous learning paradigm used here, we reared newborn chicks with two stimuli, each characterized by a different number of heterogeneous (for color, size, and shape) elements with food was found near one of the two stimuli. At testing chicks were presented with stimuli depicting novel elements (for color, size, and shape) representing either the numerosities associated with food or those that were not. The chicks approached the number associated with food in the 5 vs. 10 and 10 vs. 20 comparisons, both when quantitative cues were unavailable (stimuli were of random sizes) or being controlled, but failed in discriminating 6 vs. 9 (Rugani, Vallortigara, & Regolin, 2013). This confirms that the AMS can process large numbers but it remains to be explained why the 6 vs. 9 comparison was discriminated in the present work. We believe that this difference is related to the stimuli characteristics (homogeneous vs. heterogeneous) and to the related possibility of using nonnumerical cues. Indeed, the use of heterogeneous stimuli in the previous article allowed us to exclude the use of nonnumerical cues. In contrast, in this work the use of elements all identical in the comparison 6 vs. 9 made it possible for the chicks to rely on numerical, as well as on nonnumerical cues. In accordance with this explanation, our past results indicated that when the chicks were required to discriminate between homogeneous sets of imprinting objects (objects to which they were exposed for 3 days before the testing) they succeeded in a 6 vs. 9 comparison, solely when quantitative and numerical cues were available, but not when the overall perimeter or area were controlled for (Rugani et al., 2011).

To summarize, we think that the modality of stimuli presentation rather than the numerousness per se can elicit processing by either system. When attention is focused on the single elements of a set, the representation is supported by the OFS whereas when the attention is focused on the overall set, the representation is performed by the AMS.

Taken together, our findings suggest that there is a continuity in processing small and large sets by chicks, proving that "number sense" (Dehaene, 1997) is available very early even in nonhuman animals. That the *AMS* functions for both small and large numbers is in accordance with the hypothesis of Hyde and Spelke (2011), who argued that this mechanism is available very early even in animals. Last but not least, our findings add a further piece of evidence in opposition of the last resort theory even in very young animals. The "last resort" strategy hypothesis, originally proposed by Davis and Memmott (1982), argues that although animals are capable of tracking numbers, they fail to do so when other more salient cues (i.e., quantitative variables) are available. A large body of evidence has instead demonstrated that adult animals and young children without any specific training spontaneously focus on numbers even when other cues are available, (e.g., Cantlon & Brannon, 2007; Hauser, MacNeilage, & Ware, 1996). This is the first time to our knowledge that it has been demonstrated for large numbers (when quantitative cues were being controlled) in very young animals. Numbers appear to be extremely significant from both a phylogenetic and developmental point of view.

Even if a "number sense" strategy is precociously available in animals along the entire numerical continuum, abstract mathematical logic remains a prerogative of our species. Representation of numbers by the AMS seems to be the building block upon which only our species, with the acquisition of language, uses to construct the abstract mathematical logic that is uniquely human (Gallistel & Gelman, 1992).

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Correction to Rugani, Vallortigara, and Regolin (2013)

In the article “From Small to Large: Numerical Discrimination by Young Domestic Chicks (*Gallus gallus*)” by Rosa Rugani, Giorgio Vallortigara, and Lucia Regolin (*Journal of Comparative Psychology*, Vol. 128, No. 2, pp. 163–171), the link directing readers to the supplemental material was missing. Supplemental material for this article is available at: http://dx.doi.org/10.1037/a0034513.supp. All versions of this article have been corrected.

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