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A symmetry-based mechanism for perceptual grouping in preverbal infants

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Newborn chicks can solve complex numerical discriminations through a purely perceptual mechanism based on the possibility of creating all equal-sized subsets. The present work investigates whether this is a prerogative of precocial birds or whether an analogous mechanism can be found in humans. We familiarized 8-month-olds with sets of even numerosities (i.e., decomposable in equal-sized subsets), and then we tested them for their spontaneous preference between two novel sets, one that cannot be divided into equal-sized subsets (i.e., a prime numerosity) and one decomposable in equal-sized subsets (i.e., a non-prime odd numerosity). Infants were tested with either the 7vs.9 comparison (i.e., the prime being smaller) or the 9vs.11 comparison (i.e., the prime being larger). Infants oriented their gaze more often toward the prime set of elements, irrespective of whether it was smaller or larger in the comparison, similar to the preference observed in baby chicks. Overall, our results suggest an early-emerging perceptual mechanism that can support complex numerical discriminations, that might be shared between distantly related and ecologically different species.

Keywords Perceptual grouping, Analogous mechanisms, Early predispositions, Infants, Comparative Psychology, Numerical discrimination

A previous study showed that newly hatched domestic chicks (*Gallus gallus*) could solve complex discriminations between two sets of different numerosity via a non-numerical perceptual mechanism[1]. Within 24 h from hatching chicks were individually exposed to sets of even numerosities (i.e., 4, 6, 10, 12 elements) and tested for their preference (measured as inspection time while the chick was free to move in an arena) between two novel sets: a non-prime odd and a prime numerosity. Chicks discriminated between the two sets, preferring the group of 7 elements in the 7vs9 comparison, and that of 11 elements in the 9vs11 comparison. These results were ascribed to a perceptual mechanism based on the detection of symmetrical vs. asymmetrical grouping, i.e. the possibility (or the impossibility) of disassembling a group of objects into numerically identical subgroups[1,2]. For instance, while 9 can be symmetrically divided into three groups of three elements each (3 + 3 + 3) in the case of 7 for each permutation there will always be at least an element of imbalance (e.g., 3 + 3 + 1; 2 + 2 + 3, 3 + 4). The employed discriminations were extremely difficult to solve via numerical processing for baby chicks, both in terms of the employed numerosities[3,4] and their ratio[4,5], and as in both cases chicks inspected longer the set of a prime numerosity irrespective of its relative numerical magnitude (being it the smaller – in the 7vs.9, or the larger – in the 9vs.11 comparison), the results were interpreted as a preference for the stimulus regarded as perceptually novel with respect to the familiar sets (the even numerosities experienced during habituation). Non-prime odd numerosities, like even numerosities, can be symmetrically grouped, while primes always result in an asymmetrical grouping. This may suggest the use of perceptual grouping as a spontaneous and early available mechanism. Such a mechanism could enable mathematically naïve subjects to solve numerical discriminations by exploiting the perceptual features of the stimuli. This hypothesis was supported in the animal model by the fact that presenting sets as already grouped (using different colors for the subsets) enhanced chicks' performance, enabling more complex discriminations (i.e., 13vs15) which they otherwise failed. This stresses the relevance of perceptual (rather than numerical) features in this task[1,2]. Altogether, this data hints at a spontaneously employed mechanism available at the earliest stages of life at least in the domestic chicken. Evidence from chicks enticed the idea that this mechanism may also be early available in humans.

Interestingly, adult humans are faster at enumerating a set of elements when presented into equal-sized subsets (symmetrical grouping), while we are slower at enumerating numbers not divided into same-sized subsets[6]. Given the vast phylogenetic distance (the last common ancestor between mammals and birds dates

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around 300 million years ago[7]), and the different ecological niches (i.e., chicks are a precocial species while human infants are altricial) the presence of similar mechanisms in the two species may be particularly insightful. For example, it would cast some light on the ultimate function of this ability and its role in the development of more sophisticated cognitive mechanisms appearing in humans later in life.

Human infants and domestic chicks are known to share analogous early-emerging cognitive or perceptual mechanisms, such as intuitive physical reasoning[8,9], sensitivity to animacy[10,11], and biological motion[12,13]. From a comparative perspective, we can assume that similar predispositions evolved in both species to cope with similar relevant environmental pressures. In the case of chicks' symmetry-based perceptual mechanisms, there may be independence between mathematical ability and perceptual grouping, leaving open the possibility of an early emergence of the latter. This view puts forward the idea of (pre-existing) perceptual principles that can allow infants to distinguish different sets of elements, without calling on numerical abilities. Indeed, there are other instances, in which a non-numerical mechanism may support numerical processing, as in the case of the Object File System[14,15], or the Object Individuation[16,17]. This enables us to temporarily store mental representations of specific objects (or 'files'), which can include details like the object's shape, color, position, and motion. Each object is represented individually, but the system has a storage limit of 3 to 4 objects. While the Object File System is primarily involved in visual attention and working memory, it also supports the rapid and accurate recognition of small quantities. By representing each item separately, the system allows for an immediate grasping of quantities within its capacity limit.

Prior research by Gestalt adopted a nativist framework, asserting that perceptual organization is automatic and present at birth[18–20]. Other theorists assumed that a variety of inherent and learned processes work in conjunction to generate a perceptual organization[8,21–23]. Moreover, there is no doubt that newborns apply the grouping principle in perceptual organization. Infants, as young as newborns, are sensitive to the classic grouping principle of luminance similarity[24,25], as well as preverbal infants are to other organizational principles, including common region[26], connectedness[27,28], good continuation[23,29,30], and proximity[31].

In the present study, we test whether infants, similar to young chicks, can differentiate among two sets of elements based on the possibility (or impossibility) of decomposing the set into same-size subsets (symmetrical grouping). Specifically, here we investigate whether eight-month-old infants, like young chicks[7,8], possess a spontaneous perceptual mechanism for discriminating sets of elements. We hypothesized that infants, after being familiarized with sets of even numerosities would preferentially inspect novel numerosities that cannot be sub-grouped into equal-sized subsets (i.e., prime numerosities) rather than sets of elements allowing for symmetrical grouping (i.e., composite numerosities, such as non-prime odd numerosities). To test our hypothesis, following familiarization to sets of even numerosities, infants were presented with a preferential-looking task to assess discrimination among two sets: a prime number of elements (i.e., 7 or 11) and an odd non-prime number of elements (i.e., 9). The employed numerosities are the same as the original study with chicks[1] and were chosen as they are unlikely discriminated via a numerical strategy: they both involve large numerosities and high numerical ratios (0.78 and 0.82, respectively). The numerical ratio constitutes an index of complexity of the discrimination, defined as the ratio between the smaller and the larger set in the comparison. The closer to 1, the more difficult the discrimination. Infants usually fail in discriminations with ratios equal to, or above 0.67[32–36]. The free-looking task is very similar to the chicks' free-choice task, as both species underwent a familiarization phase and at the test could freely choose among two novel stimuli.

Discussion

In the present study, we tested for the presence of a symmetry-based perceptual grouping mechanism in human infants, based on previous evidence from a non-human species, the domestic chicken (*Gallus gallus*). We show that 8-month-old infants following familiarization to sets of even numerosity perform similarly to chicks, preferring the prime over the composite set of elements. Thus, preverbal infants, like chicks, can discriminate between different sets of elements, and they might likely do so based on their perceptual features. Alternative explanations based on number or quantity-based strategies for solving the task are unlikely. First, the comparisons used in the test are considered very hard to discriminate both in terms of set size and numerical ratio (see introduction). Additionally, a number-based strategy would not explain the direction of the choice, as infants preferred the prime over the composite set irrespective of its numerical magnitude, i.e., both when this was the smaller (7vs.9) or the larger (9vs.11) of the comparison[1].

We could also consider alternative explanations for our data. For instance, one possibility could be that infants avoid the set of 9 elements, yet to our knowledge, there is no evidence for a predisposed avoidance toward sets of nine elements (or any other size), and it would be difficult to hypothesize an adaptive value for it. We should also consider the possibility that infants responded to novelty with respect to familiar stimuli: it has been shown that 6-month-old infants can represent the frequency distribution of variable numerical input and use it to guide their preference for numerically novel sets[37]. In the case of our study, the average numerosity resulting from the familiarization stimuli is 8, thus a preference for numerical novelty could explain infants' choice of 11 in 9vs.11 but not the choice of 7 in 7vs.9, as in this latter case both tested sets are equally distant from the average familiar numerosity (assuming a linear distribution of numbers representation, as suggested by empirical evidence on babies[38–40]). In the case of a logarithmic distribution of numerosities, 7 would indeed result as more distant from 8 than 9, but this possibility is very unlikely as it implies that infants can compute and compare minute numerical differences, in the order of a few thousandths. In sum, we believe that our results support the hypothesis of infants relying on perceptual (rather than numerical) cues, similar to chicks.

As for baby chicks, infants' preference for the prime over the composite set likely depends on the familiarization experience. Infants had been habituated to even numerosities (which are composite, that is decomposable in equal-sized subsets). The non-prime odd numerosity seen at the test is also composite, hence perceptually more similar to the familiar numerosities. For instance, 6 can be symmetrically grouped as 3 + 3 or 2 + 2 + 2; similarly, the odd number 9 can be disassembled into 3 + 3 + 3, also symmetrical. On the contrary, the prime number 7 can only be grouped asymmetrically, as at least one of the resulting subsets will comprise a different numerosity, such as 3 + 3 + 1 or 2 + 2 + 3. Therefore our results could be explained by infants' preference for novelty and/or asymmetry[41–43].

Interestingly, we found no effect on the total fixation times (TFT) but an overall preference for the prime over the composite sets in the number of orientations (OR). This difference could be due to each index reflecting a separate attentional system, both in terms of the function they serve[44–47], and their developmental trajectory[16,46,48]. In particular, it has been shown that TFT is an index of attentional holding, whereas OR is a proxy of orienting of attention[44–46,48–50]. Infants might show enhanced TFT or OR depending on the type of looking time paradigm. Previous studies on infants' sensitivity to numerosities utilized habituation[34,35], change detection task[36,37], or cross-modal paradigm[17,32,33], so different visual behaviors could be expected, such as in holding (i.e., total looking time; 17, 33,34,35,37) or orienting (i.e., head-turn preference;32,36) attention. In this study, following familiarization trials, infants were presented with a preferential-looking task, in which they were asked to orient their eyes to two sets of elements (prime vs. non-prime odd numerosities) to discriminate them, without keeping their eyes locked to the two groups to count their elements.

We believe that our data contribute a first important step for exploring a perceptual mechanism that supports numerical discriminations, suggesting independence between mathematical ability and perceptual grouping. Additionally, from a comparative perspective, these findings strengthen our proposal that there can be an early-emerging perceptual principle that facilitates numerical perception across different species[1,2]. The symmetry-based grouping could rely on a perceptual principle that has been built into the species as a result of the benefits it confers for instance in guiding perception of group size (i.e., larger vs. smaller groups) for social inferences, like social dominance[51,52], or fair distribution of resources[49]. Hence, the ability to capitalize on grouping cues may have played an important adaptive function, as if a rudimentary perceptual principle helps or replaces in more difficult contexts the initial numerical knowledge. From a developmental perspective, the current results hint at perceptual grouping as an early-emerging mechanism, in line with prior findings that infants, as young as 3 months of age, can use a variety of static grouping principles, such as similarity, proximity, good continuation[23]. Also, there is evidence that perceptual grouping might subserve numerical cognition at 5 months of age[53], and act as a powerful learning mechanism, biasing infants' attention and expectations about the environment[54].

Moreover, these findings are in line with prior literature on infants' visual attention[44,45,47] and suggest that the number of orientations could be a good index for comparative studies. Further studies should be devoted to grasp a better understanding of the emergence and functioning of such a mechanism, both by testing infants at a younger age and by providing a replication of the current findings. From a more applicative perspective, it could also be possible to investigate whether perceptual grouping constitutes a starting point for designing biologically grounded interventions in the case of impairments related to numerical abilities, as in the case of dyscalculia[55,56].

To conclude, the presence of an analogous mechanism in two distantly related and ecologically diverse species, such as humans and domestic chicks, is usually considered a possible instance of convergent evolution. In our case, and if further confirmed, this would highlight the underlying biological relevance of symmetry-based grouping. It is yet to be understood whether this constitutes a specialized mechanism directly selected for detecting symmetrical patterns or, rather, it is the byproduct of the selection of a different biologically relevant trait, for example, visual processing and categorization of complex visual patterns. Regardless of its origin, our results pave the way for further investigations aimed at clarifying how symmetry-based grouping supports number discrimination in infants and how such a predisposed and intuitive perceptual-based mechanism can constitute a building block for the later development of more complex numerical cognition.

Methods

Ethical statement

The recruitment period was between the end of March 2022 to the end of May 2022. The study protocol was approved by the Ethics Committee of the University of Trento (2022-001) and informed written consent was obtained from the mother of each infant prior to the participation in the study. All procedures were performed in accordance with relevant guidelines and regulations.

Participants

We tested a total of forty-eight infants. Subjects were randomly assigned to one of two possible conditions, i.e., the 7vs.9 comparison ($n = 24$; mean age = 242 days; range = 230 to 250 days; 12 males), or the 9vs.11 comparison ($n = 24$; mean age = 245 days; range = 231 to 253 days; 13 males). We adopted the minimal sample size based on previous studies[57–60] and in line with the restriction for accessing the laboratories following the Italian guidelines for COVID-19.

We asked the parents of the infants to complete a questionnaire about the infant's date of birth, gender, and other family information. According to the information provided by parents, all infants had a typical development of social, verbal, motor, and cognitive skills.

Nine additional infants were tested and excluded from the final sample due to fussiness ($n = 5$) or a position bias ($n = 4$) (the criterion we chose was that infants were coded as having a side bias if they looked at the same side of the screen for more than 80% of the total time in test trials).

Coding

Infants' looking behaviors were coded offline from video by a first coder, who was masked to the left-right position of the stimuli, frame by frame, and using VirtualDub software (https://www.virtualdub.org). An additional 50% of the sample was re-coded by a second coder blind to the conditions and the aims of the study.

The inter-coder agreements (Pearson correlations) with the second coder of both indexes TFT and OR were all $p_s \geq 0.95$ (see data **S1** in Supplementary information).

Stimuli and procedure

Familiarization phase

This was the same for both groups (Fig. 1A). Infants were presented with four events displaying a random sequence of stimuli comprising an even number of elements (dots). In each event, infants saw 12 stimuli in random order (see movie **S2** in Supplementary information). To rule out a possible preference of infants for rounded over angular shapes, each stimulus was a set of dots (i.e., circles) of different numerosity (i.e., 4, 6, 10, or 12) and color (i.e., red, yellow, or blue), which was presented as a random pattern and arranged within a white square. Each set remained visible for five seconds and was immediately followed by a subsequent one (with a total of 60 s for each event). Infants had to attend at least three familiarization events to be included in the analysis. A familiarization event was considered attended if infants had looked at it for at least 80% of the time, namely 48 out of 60 s[61].

Test phase

Following familiarization events, infants' discriminations and preferences were assessed using the preferential-looking paradigm, employing the procedure used in some recent infant studies[61,62]. This consisted of two trials, at the beginning of each trial a fixation cross that pulsated with a sound was presented for 1 s. Subsequently, two novel stimuli were presented together, one on the left, and one on the right side of the screen, at 25 cm from one another. As for the familiarization, each stimulus consisted of a group of dots randomly arranged within a white square, one always being a prime (either 7 or 11), and the other a composite odd set of 9 elements. After 20 s during which the stimuli remained visible on the screen, they swapped their position (Fig. 1B), to control for possible side biases. The first spatial position (left or right) of each set was counterbalanced between subjects. The spatial arrangement of the elements within each group, as well as the color of the testing stimuli (red or yellow), was counterbalanced within subjects, alternating four possible combinations.

Following Cohen's model[44,45], and the procedure used in prior infant studies using the preferential-looking paradigm[10,24,62], we considered the number of orienting responses (OR) as an index of orientation of attention, and the total fixation times (TFT) as an index of holding of attention. TFT was scored as the sum of fixation times toward each set of elements, and OR as the sum of how many times infants oriented their gazes toward either set of elements.

Data analysis

Data were analyzed using R (R 4.2.0)[41]. TFT and OT were analyzed separately. For each analysis, we ran an Akaike Information Criterion (AIC) based model selection using linear mixed models (R package lme4[50]). The full model included the dependent variable either the TFT or the OR, and as an independent variable the stimulus (prime or composite), the experimental comparison (7vs9 or 9vs11), and their interaction. Subjects were included in the model as the random effect. For what concerns TFT, the best fitting model was the one having as predictor the sole effect of the stimulus - lmer (TFT ~ stimulus + (1|subject)), having an AIC value of 1827.2. The same model resulted when analyzing OR - lmer (OR ~ stimulus + (1|subject)), with an AIC value of 454.70. Subsequently, we ran a post-hoc analysis with Bonferroni correction on the selected model (R package

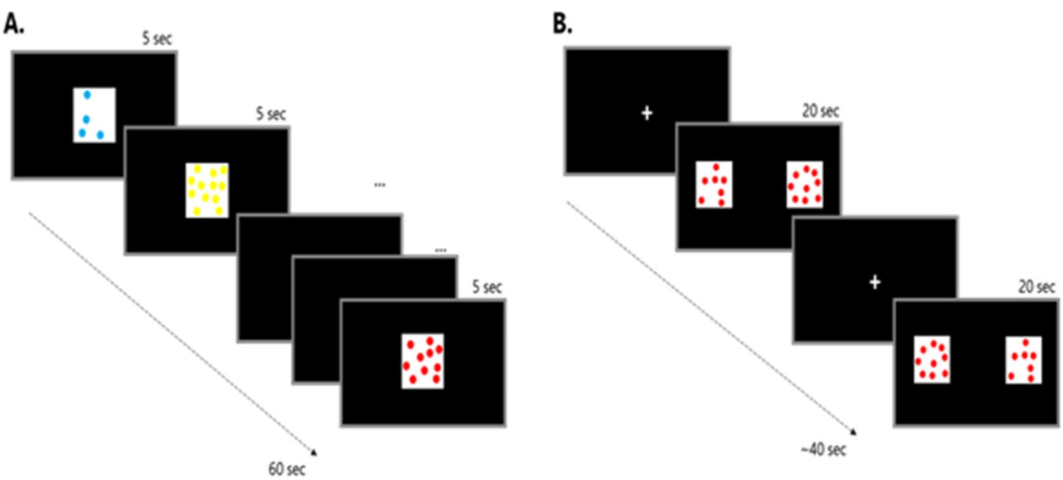

Fig. 1. The experimental paradigm: (**A**) Stimuli presentation during familiarization. Each subject saw a random sequence of sets of dots of different colors (i.e., blue, red, or yellow) and numerosity (i.e., 4, 6, 10, 12). Each set remained visible for 5 s and was immediately replaced by a subsequent one. (**B**) Stimuli presentation at test. Each subject was presented with a pair of stimuli of the same color (in this example red), one being a prime (in this example 7) and the other a composite[9] number. After 20 s, the fixation cross reappeared on the screen, and the two stimuli were swapped and presented for another 20 s.

emmeans[42] to determine the direction of the effect. We computed Cohen's d as a standardized effect-size measure using the eff_size function of emmeans[63].

Results

When analyzing TFT (Fig. 2A), the selected model was the one including the effect of the stimulus only (AIC 1827.2). Despite babies spending on average more time looking at the prime set, the difference appeared not to be significant (estimated mean difference (composite-prime) = -933 ms; SE = 480 ms, t = -1.944, $p = 0.058$). The estimated effect size for this pairwise difference is considered small (d = 0.398). When analyzing OR (Fig. 2B), the selected model was the one including the stimulus only (AIC = 454.7). Infants oriented more toward the prime over the composite stimulus (estimated mean difference (composite-prime) = -0.875; SE = 0.259, t = -3.374, $p = 0.002$) irrespective of it being the smaller or the larger of the comparison. The effect size for this pairwise difference is considered moderate (d = 0.694).

Lastly, when visually inspecting the data with a scatterplot for both TFT (Fig. 3A) and OR (Fig. 3B), it is possible to notice that the majority of data points fall under the diagonal toward the prime set, thus suggesting that also when considering individual subjects there is a trend toward to such stimuli.

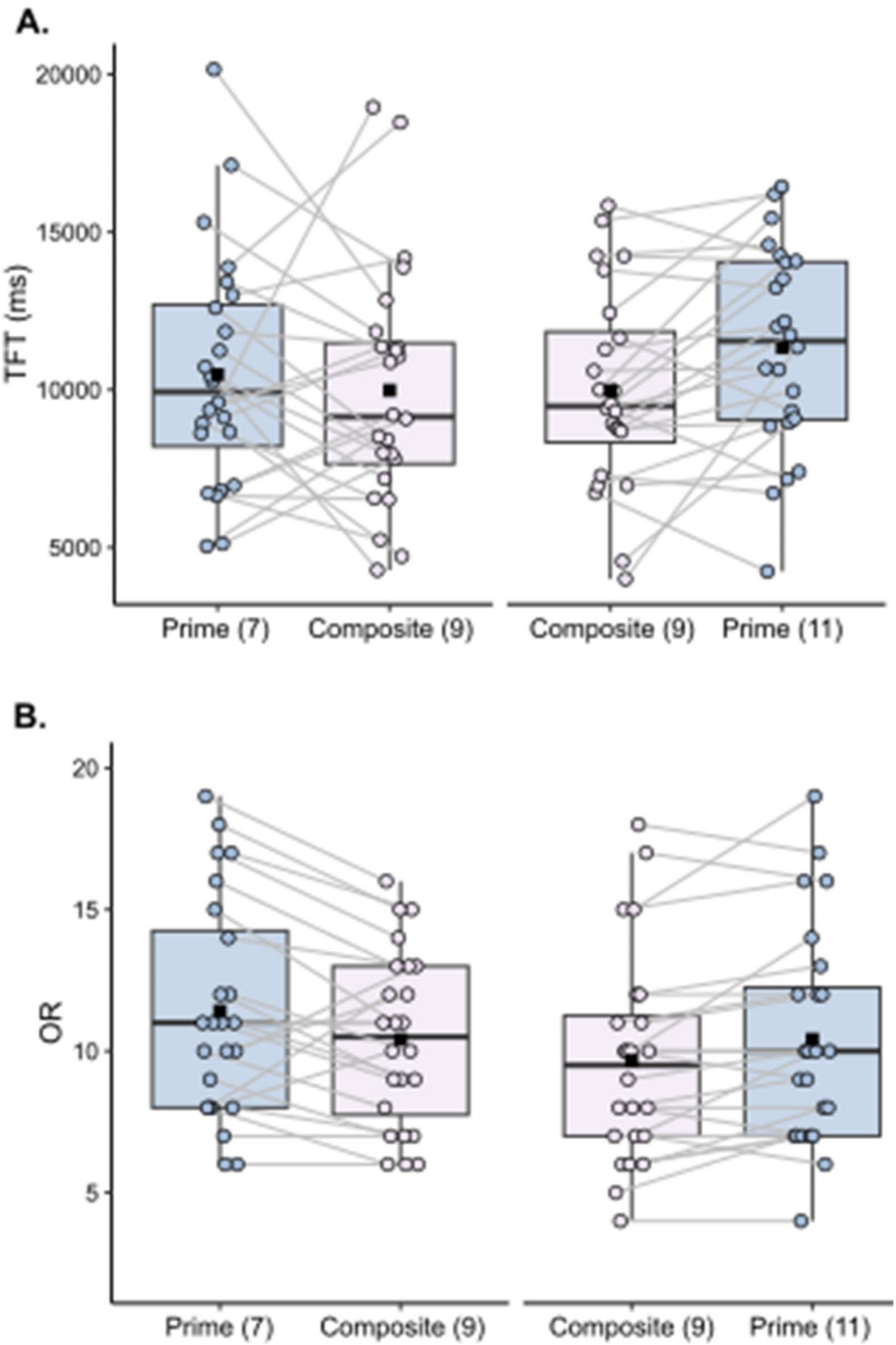

Fig. 2. Results: The x-axis displays the test stimuli in each condition: on the left the 7vs9 comparison, and on the right the 9vs11 comparison. Each colored square represents the performance of a single subject, with the performance of the same subjects being connected by the grey line. The black square represents the mean, and the horizontal line represents the median. (**A**) Total Fixation Times (TFT) in milliseconds. Infants fail both discriminations and behave at chance. (**B**) Number of Orientations (OR). Infants show higher OR for the prime over the composite numerosity.

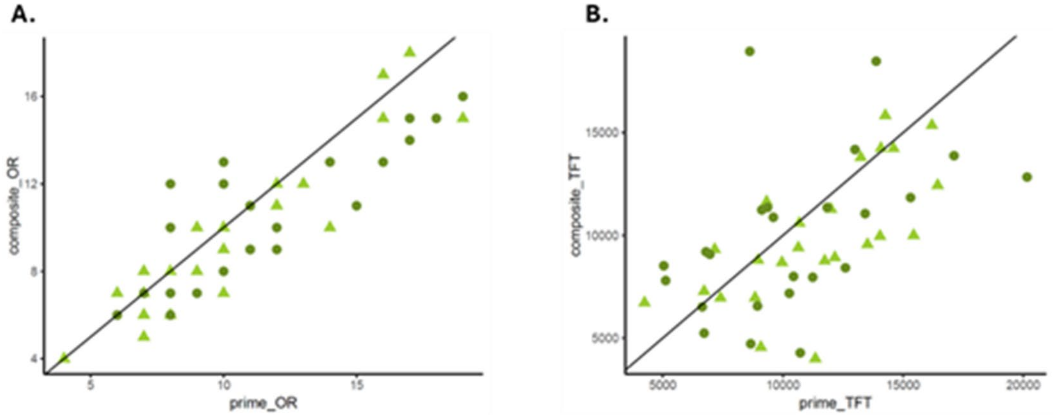

Fig. 3. Results: Scatterplot of individual performance when considering composite (y-axis) vs. prime (x-axis) sets. The dark green dots refer to the 7vs9 comparison; the light green triangles refer to the 9vs11 comparison. (**A**) Scatterplot of orienting responses (OR). (**B**) Scatterplot of total fixation times (TFT).

Data availability

Data is provided within the manuscript or supplementary information files.

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Author contributions

A.G., M.L. and L.R. contributed to the design and implementation of the research. A.G. carried out the experiment, M.L. analyzedthe data, and L.R. supervised the project. A.G. and M.L. wrote the manuscript in consultation with L.R.

Declarations

Competing interests
The authors declare no competing interests.

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