A mental number line in human newborns

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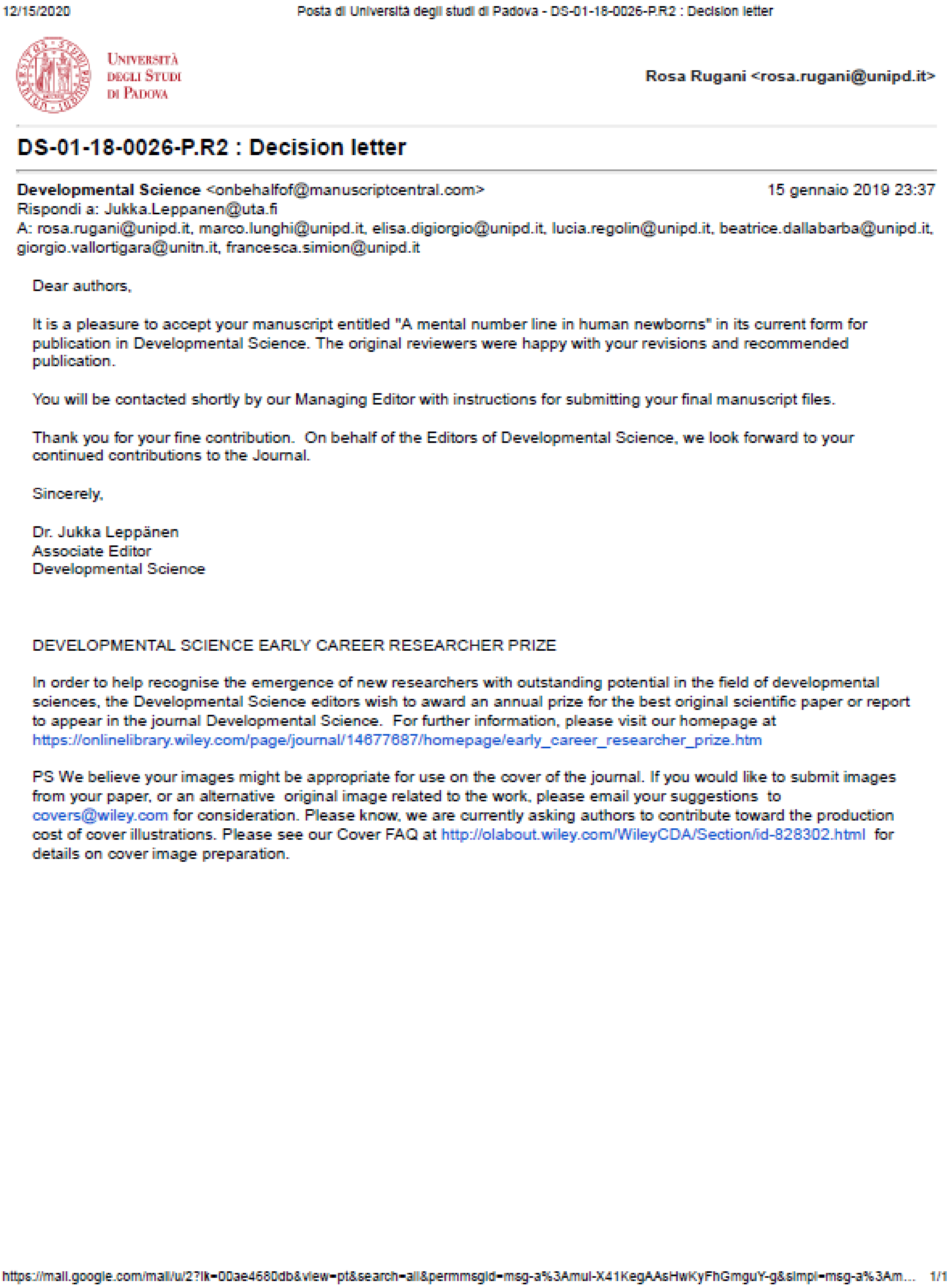

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It is a pleasure to accept your manuscript entitled "A mental number line in human newborns" in its current form for publication in Developmental Science. The original reviewers were happy with your revisions and recommended publication.

You will be contacted shortly by our Managing Editor with instructions for submitting your final manuscript files.

Thank you for your fine contribution. On behalf of the Editors of Developmental Science, we look forward to your continued contributions to the Journal.

Sincerely,

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Title: A mental number line in human newborns

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Research highlights

- Humans represent numbers on a left to right oriented mental number line, with smaller numbers located on the left and larger ones on the right.
- The cultural *vs.* biological origin of the mental number line is a strongly debated issue.
- After being habituated to a certain number, hour-old neonates associated a smaller number with the left and a larger number with the right side.
- This evidence demonstrates that a predisposition to map numbers onto space is present soon after birth.

Abstract

Humans represent numbers on a mental number line with smaller numbers on the left and larger numbers on the right side. A left-to right oriented spatial-numerical association, SNA, has been demonstrated in animals and infants. However, the possibility that SNA is learnt by early exposure to caregivers' directional biases is still open. We conducted two experiments: in Experiment 1 we tested whether SNA is present at birth and in Experiment 2 we studied whether it depends on the relative rather than the absolute magnitude of numerousness. Fifty-five-hour-old newborns, once habituated to a number (12), spontaneously associated a smaller number (4) with the left and a larger number (36) with the right side (Experiment 1). SNA in neonates is not absolute but relative. The same number (12) was associated with the left side rather than the right side whenever the previously experienced number was larger (36) rather than smaller (4) (Experiment 2). Control on continuous physical variables showed that the effect is specific of discrete magnitudes. These results constitute strong evidence that in our species SNA originates from pre-linguistic and biological precursors in the brain.

Key words: number space association, human newborns, SNARC, mental number line, numerical cognition, number sense.

Introduction

Non-symbolic numerical skills are widespread in the animal kingdom (Vallortigara, 2014). Pre-verbal infants (Cordes & Brannon, 2009; Izard, Sann, Spelke & Streri, 2009) and non-human species (Vallortigara, 2012) can extrapolate numerical magnitude from an array of elements, showing a non-symbolic number comprehension (Feigenson, Dehaene & Spelke, 2004; Rugani, Castiello, Priftis, Spoto & Sartori, 2017). In humans, this comprehension is present early in infancy (Cordes & Brannon, 2009) and can be assessed in adults by preventing the use of language (Cantlon & Brannon, 2007; Cordes, Gelman, Gallistel & Whalen, 2001). Both humans (Moyer & Landaeur, 1967) and animals (Cantlon & Brannon, 2007; Scarf, Hayne & Colombo, 2011) find non-symbolic numerical tasks easier as the difference between the numbers increases (distance effect) and harder as the numerical magnitude increases (size effect). These similarities are suggestive of a shared, ancient, non-verbal numerical mechanism (Cantlon & Brannon, 2007). Therefore, uniquely human mathematical abilities seem to be based on an early developing and evolutionarily ancient "number sense" (Dehaene, 2011). Recently, Leibovich et al. (2017) claimed that it would be impossible to control for all continuous physical extents (e.g., perimeter, area, size, density) in a non-symbolic numerical task, challenging the number sense theory. Leibovich and colleagues' stance should prompt reflection on what a non-symbolic number is. By definition, a non-symbolic number is the numerousness extrapolated from an array of elements (Rugani et al., 2017). Non-symbolic numerousness is likely to be part of a more general system for representing quantity, both discrete and continuous (see Gallistel, 2011). A more challenging research-line would therefore aim to disentangle the interplay between continuous-physical extents to achieve number comprehension. Therefore, in this paper we tried to provide maximally accurate controls to check for a role of continuous physical variables in our experiments.

A peculiar characteristic of numerical representation concerns the spatial coding of numbers along a left-right oriented continuum (Galton, 1880). Adults are faster in processing small numbers when responses are executed on the left side of space and faster for large numbers when responses are executed on the right side of space (spatial-numerical association of response codes, SNARC effect; Dehaene, Bossini & Giraux, 1993). Several studies suggested that the left-to-right orientation of the mental number line is an outcome of exposure to formal instruction and that the mapping of number onto space would be a by-product of culture, based on reading/writing conventions and tool use, such as rulers (Rugani & de Hevia, 2017). Native Arabic speakers show an inverted SNARC effect (Zebian, 2005), whereas people with mixed reading habits (i.e. those brought up reading both left-to-right and right-to-left) show no SNARC effect at all (Shaki, Fischer & Petrusic, 2009). However, an increasing number of studies support the idea of a biological root for the mental number line. Seven-month-old infants looked longer at increasing (e.g. 1-2-3) but not at decreasing (e.g. 3-2-1) magnitudes displayed in a left-to-right spatial orientation (de Hevia, Izard, Coubart, Spelke & Streri, 2014). Eight-month-old infants oriented their attention toward the left after having seen a small numerousness (i.e., 2), and toward the right after having seen a large numerousness (i.e., 9) (Bulf, de Hevia & Macchi-Cassia, 2015). This infant evidence clearly excludes a primary influence of verbal counting in SNA orientation. However, this could still result from a history of interactions with adults and the external world (Patro, Fischer, Nuerk & Cress, 2016). A tendency to look longer at numerousness from left-to-right has been reported in our species (de Hevia *et al.,* 2014; Izard *et al.,* 2009). However, this is only a partial evidence of the SNA, because an increase in the looking time from right-to-left has not been reported for decreasing sequences.

Also, adult Clark's nutcrackers (Rugani, Kelly, Szelest, Regolin & Vallortigara, 2010) and rhesus monkeys (Drucker & Brannon, 2014) have shown unilateral, left-to-right oriented bias in associating numerousness with space. Nevertheless, these biases could depend on continuous extents, which were not systematically controlled. A spatial representation of magnitude has been recently also found in gorillas and orangutans (Gazes, Diamond, Hope, Caillaud, Stoinski & Hampton, 2017). Interestingly, however, even if present in most of the individuals the direction of the association was either left-to-right or right-to-left oriented. Differences in orientation do not appear to be due to species or handedness, but rather to idiosyncratic experiences such as the interactions with caregivers (Gazes et al., 2017). Different evidence came from a study in cleaner fish: a lack of association between magnitudes and space was observed in this species that can be attributed to either experiential or evolutionary factors (Triki & Bshary, 2018). Clearly, other species of lower vertebrates need to be tested.

It seems that spatial-numerical association emerges differentially depending on the task (see e.g. Patro, Nuerk, Cress, & Haman, 2014, Patro et al., 2016), as a consequence it is not simple to understand which task better reflects the human mental number line. On one hand several early spatial-numerical associations concern mostly ordinal tasks (e.g. deHevia & Spelke, 2010; Drucker & Brannon 2014; Opfer Thompson, & Furlong, 2011; Rugani, Regolin & Vallortigara, 2007). Searching for items in a fronto-parallel arranged series of numbered items, 4-year-old children expected numbers to be ordered from left-to-right (Opfer et al., 2011). After learning to find an object in a sagittal series of objects, two and three-year-old children were tested on a 90° transposed display (i.e. fronto-parallel arranged) and started to count from the left end. This bias occurred when the objects were numerically labeled and not when they were not labeled or when they were alphabetically labeled, showing the peculiarity of numbers to prompt a left-to-right spatial mapping (McCrink, Perez, & Baruch, 2017). A tendency to count from left to right has been found also in non-human animals, using a different kind of ordinal task. Animals were trained to identify a target element (e.g. the 4th) in a sagittal-oriented series of identical elements. During the test phase they were required to respond to an identical series but rotated by 90°. The correct options were actually two: the target from the left and the one from the right end of the series. Day-old domestic chicks (Rugani et al., 2007), adult Clark's nutcrackers (Rugani et al., 2010) and adult monkeys (Drucker & Brannon, 2014) selected the target from the left end most often. On the other hand, this left-sided bias could either be related to the association between numbers and space or to a general bias in the allocation of spatial attention (Rugani et al., 2011). This phenomenon, known as "pseudoneglect", was first described in humans and reflects the fact that in many cases we primarily attend to objects in the left side of space (Bowers & Heilman, 1980). More recently, a selective allocation of spatial attention to the left hemifield has been also identified in adult pigeons and chicks (Diekamp et al., 2005; Regolin, 2006). The left-to-right tendency in the ordinal task could be both attributed to the SNA as well as to a pseudoneglect phenomenon. On the other hand, other kinds of tasks have been designed to highlight spatial bias to respond to arithmetic outcomes (Patro & Haman, 2012; Rugani, Rosa-Salva, & Regolin, 2014) and to the response time to numerals (Adachi, 2014).

To date a complete evidence of a non-verbal SNARC-like phenomenon has only been provided in domestic chicks, which preferentially respond to small numbers on the left side and to large numbers on the right side of space (Rugani, Vallortigara, Priftis & Regolin, 2015a). Chicks associated a same non-symbolic number (i.e., an array of 8 squares) either with the left side, in the 8-32 range, or with the right side, in the 2-8 range. Such relativity of SNA is a fundamental characteristic of the human mental number line.

In this study, to avoid the influence of pseudoneglect phenomena, to ascertain the relativity of the SNA and its dependence on the number magnitude, we used a new experimental paradigm, inspired by Rugani and colleagues' study (2015), that can be easily adapted to the exceptionally young age of our human participants. In addition to this, this paradigm best reflects all the aspects that have been described in the adult-humans mental number line literature, which focused on the SNARC effect and estimation of a position on the number-line. Both effects are mostly documented in human adults tested with symbolic numerals (Dehaene, 2011). However, it is not yet clear if they may be generalized onto a non-symbolic numerical system. The underlying mechanism at the basis of chicks' SNARC-like effect might differ from the one that drives the effect in humans (Shaki *et al.,* 2009). Birds have laterally placed eyes, complete nerve crossings at the optic chiasm and minimal interhemispheric connections, giving rise to a strong lateralization of function in everyday behavior (Rogers, Vallortigara & Andrews, 2013). Humans, in contrast, like other primates, have frontally placed eyes, only partially crossing nerves at the optic chiasm and strong interhemispheric connectivity. As a result, they show visual lateralization only in restricted conditions of vision (e.g. lateral presentation of briefly-presented stimuli) (Ocklenburg, 2017). The only way to discover the root of the human mental number line is to explore whether human newborns, under minimal or no exposure to adults' scanning biases, manifest SNA. Recently it has been demonstrated that 3-day-old newborns associate continuous quantitative extents with space (de Hevia et al*.*, 2017).

The aim of this study is twofold. The first aim is to improve our knowledge on the origin of SNA, while exploring the role of the main continuous physical variables (i.e. area, perimeter, and occupancy) in the visual domain. A second aim consists in investigating whether the association between a given number and space is triggered by absolute rather than relative magnitude. Broadly speaking, if the SNA depends on the absolute numerical value, this means that if a number is considered small, it will always be associated with the left space; *vice versa* if a number is considered large it will always be associated with the right space. On the other hand, if the SNA depends on the relative numerical magnitude, this means that it is related to the magnitude of the given number within a considered numerical interval, or in comparison to another number.

Experiment 1: The origin of the SNARC effect

Method

Participants

Twenty-four (10 males) full-term Caucasian newborns (Mean = 51 h, SD = 28.16, range 12 – 117 h), were selected from the maternity ward of the Pediatric Clinic of the University of Padova. We computed the sample size with G*Power. Using an effect size of .77 (considered a good effect size in psychological studies, see Cohen 1988; Sawilowsky, 2009) and with the power of the test of .80, we obtained a total sample size of 12 (alpha error .05). Moreover, this sample size is very similar to previous studies with newborns (Craighero, Leo, Umiltà & Simion, 2011; Di Giorgio, Leo, Pascalis & Simion, 2012). All participants met the normal delivery screening criteria, had a mean birth weight of 3087.92 g (SD = 494.16), and an Apgar score of 9 at 5 min.

An additional fourteen newborns (9 males) were tested but they were not included in the final sample because i) n=4 did not complete the test, because of a change in their state, ii) n=9 showed a positional bias, i.e. they looked in one direction for more than 80% of the total fixation time recorded both during the habituation and the test phase separately (Bulf, Johnson, & Valenza, 2011; Di Giorgio, Lunghi, Simion & Vallortigara, 2017, and, iii) n=1 was considered outlier. Outliers were identified on total fixation times toward stimuli, using SPSS software (criterion: 1.5×IQR-Interquartile range).

All newborns were tested only if awake and in an alert state (Prechtl & O'Brien, 1982), and after the parents had provided informed consent. All experimental procedures were approved by the Pediatric Clinic of the University of Padova (Protocol number 19147).

Stimuli

Habituation and test stimuli consisted of static two-dimensional images. They were horizontally aligned and presented bilaterally on the left and on the right side from the center of the screen. All stimuli contained a well-defined number of black square elements with an average luminance 0.4 cd/m^2, depicted within a white square area of 17.5 cm x 17.5 cm (695 x 695 pixels), subtending a visual angle of 30.3° x 30.3° (average luminance 103 cd/m^2). The distance between the two stimuli was of 8.50 cm (13.65°). The number, the dimension and the position of the elements varied, within each stimulus, as a function of the experimental conditions.

For the habituation phase, we used five stimuli. Each stimulus was an array composed of 12 black square elements, differing in their spatial position. Each black element measured 1.1 cm x 1.1 cm (43.67 x 43.67 pixels), subtending a visual angle of 2.1° x 2.1°. The five stimuli were presented in a random sequence. Each stimulus lasted 500 ms without any interval between two consecutive stimuli. The five stimuli were randomly presented in a loop in order to convey a dynamic change of position of the elements. Habituation phase lasted until newborns reached the habituation criterion, which was automatically computed by E-prime software.

We decided to employ five stimuli during the habituation phase in order to i) attract and maintain newborns' attention and ii) prevent the newborns from identifying the stimuli on the basis of the spatial disposition of the black squares.

After the habituation phase with the number 12, a sequence of two different trials, counterbalanced between participants, was administered. In each test trial the same stimulus was simultaneously presented on the left and on the right side of the monitor. Half of the newborns had the small number in the first test trial and the large number in the second one (4-36). The other half had the large number in the first test trial and the small number in the second one (36-4). Test stimuli comprised a number of elements which were either smaller (4 black squares, for the small number test trial) or larger (36 black squares, for the large number test trial) than the number experienced during habituation (i.e., 12). Also in the test stimuli, each element measured 1.1 x 1.1 cm (43.67 x 43.67 pixels), subtending a visual angle of 2.1° x 2.1°.

We decided to use these squares dimensions and the distances between them taking in account neonatal visual acuity, which is about 1 cycle/degree (Mayer, Beiser, Warner, Pratt, Raye, & Lang, 1995). As reported by Leat and colleagues (2009): "There have been numerous studies […], showing that visual acuity (VA) develops from about 1 cycle/degree (this is often taken to be equivalent to 6/180 Snellen = 0.0333 decimal acuity) in the newborn to 2.6-12 cycle/degree at one year" (pp. 21) (Leat,Yadav, & Irving, 2009). Therefore, in light of this, in both our experiments, the stimuli dimension was adequate for newborns to separately process each square as a discrete element.

Apparatus and procedures

We employed an infant-control habituation procedure (Horowitz, Paden, Bhama & Self, 1972; Sokolov, 1963). Stimuli presentation and data collection were performed using E-Prime 2.0.

The baby sat on an experimenter's lap at a distance of 30 cm from the computer screen and white curtains were drawn on both sides of the newborn to prevent interference from irrelevant distractors. The stimuli were displayed on an Apple LED Cinema Display (Flat Panel 30″) computer monitor (refresh rate = 60 Hz, resolution 2560 x 1600 pixels).

The experimenter holding the baby was naive to the test hypothesis and was instructed to fix her/his gaze on a monitor throughout the experimental session to check the position of the baby was aligned with the centre of the screen. Above the computer screen, the video camera recorded the eye movements of the newborn to control their looking behavior on-line and to allow off-line coding of their fixations.

At the beginning of each experiment, a red disc on a black background appeared to attract the newborn's gaze to the centre of the monitor (i.e., fixation point). In a continuous fashion, the disc changed in size from small (diameter = 1.8 cm) to large (diameter = 2.5 cm), and vice-versa until the newborn's gaze was properly aligned with the red disc. The red disc blinked at a rate of 300 ms on, and 300 ms off. The sequence of trials was started by a second experimenter who watched the newborn's eyes through the monitor. When the newborn's gaze was aligned with the red disk, the second experimenter, naïve to the hypothesis, pressed a key that automatically turned off the central disc and activated the onset of the stimuli, thereby initiating the sequence of trials.

The paradigm comprised the habituation phase and the test trials, in which two identical stimuli were presented side-by-side. In the habituation phase, the loop of the stimuli remained on the screen until the habituation criterion had been reached. Newborns were judged to have habituated when, from the fourth fixation onward, the sum of any three consecutive fixations was 50% or less of the total of the first three fixations (Slater, Earle, Morison & Rose, 1985). A bilateral, rather than a central presentation was selected for two reasons: i) when newborns look at a centrally presented stimulus, it is difficult for a coder to decide whether they are actually looking at the stimulus or simply not moving their eyes from the central position; ii) at birth, the photoreceptors in the central fovea are very immature, resulting in poor vision in the central area of the visual field (Abramov et al., 1982; Atkinson & Braddick, 1989). A test trial ended when newborns did not fixate on the display for at least 10 s.

In the present study, for the convenience of explanation, we calculated the percentage index using the stimulus on the left side for all experimental conditions. Therefore, scores significantly below

50% indicated a visual preference for the stimulus on the right side of the screen, whereas scores significantly above 50% indicated a preference for the stimulus on the left side. Other two coders, independently of each other and blind to the stimuli presented, performed an offline analysis of the videos by coding newborns' eye movements frame by- frame. The mean estimated reliability between observers was Pearson's $r = 0.93$, $p < 0.001$, computed on 31 out of 48 newborns (64.58%).

Data Scoring and Statistical Analyses

The dependent variable that we measured, as in previous studies (Di Giorgio et al., 2012; Valenza, Simion, Macchi-Cassia & Umiltà, 1996) was the percentage of visual preference (Cohen, 1972), that is the length of time for which each newborn looked at the stimulus presented on the left side divided by the total time spent looking at both stimuli in each test trial, X 100.

Data of Experiment 1 were analyzed as follows:

i) a first analysis was conducted on the percentage of total fixation time towards the left position during the habituation phase, to control for any spontaneous a-priori preference for a specific position (i.e., spatial biases);

ii) a repeated measures ANOVA with Test Trials Order of stimuli presentation (4-36 and 36-4) as a between-participants factor and Stimulus (4*vs.*4 and 36*vs.*36) as within-participants factor on the percentage of total fixation time toward the left stimulus was carried out;

iii) a two-sided one sample t-test on the percentage of total fixation time in the first test trial was carried out.

Data were analyzed using SPSS software.

Results

All newborns included in the final sample reached the habituation criterion and looked equally at the two stimuli $t_{23} = 0.56$, $p = 0.582$ ($M_{\text{left}} = 52.25$, $SD = 19.73$, Cohen's $d = 0.11$, see Fig.1).

We carried out a repeated measures ANOVA with Test Trial Order (4-36 and 36-4) as a between-participants factor and Stimulus (4*vs.*4 and 36*vs.*36) as within-participants factor on the percentage of total fixation time toward left stimulus. The analysis revealed a significant main effect of Stimulus, $F_{1,22} = 14.29$, $p < 0.001$, $\eta^2_p = 0.48$ (number 4, $M_{left} = 64.04$, SD = 18.65; number 36, $M_{left} = 36.08$, SD = 22.85). No other main effect or interaction reached the statistical significance. Newborns looked significantly longer than chance level (50%) at the left-stimulus in the 4*vs.*4 trials ($t_{23} = 3.69$, $p = 0.001$, Cohen's $d = 0.75$), and at the right-stimulus in the 36*vs.*36 trials ($t_{23} = -2.98$, $p = 0.007$, Cohen's $d = 0.61$). Interestingly enough, the spatial bias that emerged during testing was not present during the habituation, where newborns looked equally at the two stimuli. This indicates that the bias is caused by the previous experienced numbers. Nevertheless, the first test trial might influence newborns' performance in the second test trial, because newborns were presented with a different numerousness. On the other hand, the performance in the first test trial could be solely influenced by the number perceived during habituation phase.

To assess more directly whether habituation *per se* could affect spatial bias, we conducted a separate analysis on the first test trial. Results confirmed that when the two stimuli depicted a number smaller than 12 (4*vs.*4, Fig.1), newborns looked longer at the left-stimulus ($M_{left} = 61.25$, SD = 17.44, $t_{11} = 2.24$, $p = 0.047$, Cohen's $d = 0.65$), when the stimuli depicted a number larger than 12 (36*vs.*36, Fig.1), they looked longer at the right-stimulus ($M_{left} = 28.00$, SD = 24.68, $t_{11} = -3.09$, $p = 0.010$, Cohen's $d = 0.89$). This highlights that the numerousness perceived during habituation influences either left or right spatial association that we found in the first test trial.

These data suggest that at birth the association between small numerousness with the left side of space and large numerousness with the right side of space is already present. However, since the squares were identical in size, newborns' preferences could have been driven by numerical or by continuous physical variables (overall perimeter and overall area).

Experiment 2: The SNARC effect is relative in human newborns

In Experiment 2a and 2b, we tested for two fundamental characteristics of the SNA in newborns: i) its independence from continuous physical variables; ii) its relative nature.

To control for a possible use of continuous physical variables, we used squares of different dimensions during habituation and test trials. By controlling for the overall perimeter (the summation of perimeters of all squares depicted in the habituation and in the test stimuli was identical); this also allows to disentangle between area and number: if the overall perimeter of two arrays of two-dimensional squares is identical, an inverse correlation exists between numbers and overall area (Rugani et al., 2017).

Method

Participants

We habituated 12 neonates (Mean = 64.66 h, SD = 29.74, range 29 – 126 h; Experiment 2a) to the number 4 and a second group of 12 neonates (Mean = 52.75 h, SD = 42, range 11- 135 h, Experiment 2b) to the number 36. All participants met the normal delivery screening criteria, had a mean birth weight of 3298.12 g (SD = 542.96) and an Apgar score of 9 at 5 min.

An additional nine newborns (1 male) were tested but they were not included in the final sample because i) n = 6 did not complete the test, because of a change in their state, and ii) n = 2 were considered outliers.

Stimuli

In Experiment 2a and 2b, we equated the overall perimeter (i.e. summation of the perimeter of all black squares) of the stimuli presented in the habituation and in the test trials. At the same time, we also avoided the possibility that newborns relied on the overall area (i.e. summation of the area of all black squares). As a consequence, we obtained an inverse correlation between the overall number of elements and their overall area.

As in Experiment 1, we used five stimuli during the habituation phase. Specifically, in Experiment 2a, for the habituation phase we employed stimuli comprising 4 black squares of 3.3 cm x 3.3 cm (132 x 132 pixels), subtending a visual angle of 6.3° x 6.3°. The overall perimeter of the 4-

elements was 58.2 cm. During a single test trial, both groups of participants were presented with two identical stimuli, each depicting 12 squares, one on the left and one on the right side of the monitor.

Test trial stimuli were 12 static black squares of 1.1 x 1.1 cm and therefore, with an overall perimeter of 58.2 cm. Importantly, the overall area of the 4-element stimuli (43.6 cm^2) was larger than that of the 12-element stimuli (14.5 cm^2). If the overall area, when the overall perimeter of the stimuli is identical, was the crucial factor underlying space-number association, newborns at test would have looked longer at the stimulus on the left side.

As in Experiment 2a, in Experiment 2b the overall perimeter between the habituation stimuli and the test stimuli was identical (158.4 cm). Habituation stimuli were 36 black squares (1.1 x 1.1 cm), whereas test stimuli were 12 static black squares, measuring 3.3 x 3.3 cm. The overall area of the 36-elements stimuli (43.6 cm^2) was smaller than that of the 12-elements stimuli (130.7 cm^2). If the overall area, when the overall perimeter of the stimuli is identical, were the crucial factor underlying space-number association, newborns would have looked longer at the stimulus on the right side.

Apparatus and Procedure

The apparatus and the procedure were the same used in Experiment 1.

Data Scoring and Statistical Analyses

In Experiment 2a and 2b, we ran the following analyses:

i) we replicated the same analysis carried out in Experiment 1 during the habituation phase to control for any spontaneous a-priori preference for a specific position (i.e., spatial biases);

ii) an ANOVA with Experiment (2a and 2b) as a between-participants factor on the percentage of total fixation time toward the left stimuli was carried out, in order to test the relativity of SNA;

iii) a two-sided one sample t-test on the percentage of total fixation time was carried out.

Results

All newborns included in the final sample reached the habituation criterion. Any spatial biases for both stimuli did not reach statistical significance, neither in Experiment 2a, $t_{11} = 0.73$, $p = 0.480$ ($M_{left} = 54.25$, SD = 20.13, Cohen's $d = 0.21$, see Fig.2) nor in Experiment 2b, $t_{11} = 0.02$, $p = 0.980$ ($M_{left} = 50.17$, SD = 22.96, Cohen's $d = 0.01$, see Fig.3).

We ran an ANOVA with Experiment (2a and 2b) as a between-participants factor on the percentage of total fixation time toward the left stimuli. The analysis revealed a significant main effect of Experiment, $F_{1,22} = 19.671$, $p = 0.001$, $\eta^2_p = 0.472$. The neonates habituated with number 4 looked significantly longer than chance level (50%) at the 12-elements on the right side ($M_{left} = 30.17$, SD = 22.85, $t_{11} = -3.01$, $p = 0.012$, Cohen's $d = 0.87$, Fig. 2). The neonates habituated with number 36 looked longer at the 12-elements on the left side ($M_{left} = 75.08$, SD = 26.62, $t_{11} = 3.26$, $p = 0.008$, Cohen's $d = 0.94$, Fig. 3). These results show that SNA i) depends on number and not on other continuous physical variables, ii) is relative to the considered numerical range.

Discussion

The ultimate nature (cultural *vs.* biological) of the orientation of the mental number line is a strongly debated theoretical issue. On the one hand it has been suggested that the mental number line emerges as a result of exposure to formal instruction and culture (Patro et al., 2016; Shaki et al., 2009). On the other hand, an increasing amount of evidence has shown that pre-verbal infants and non-human animals associate numerousness with space, suggesting that the mental number line originates from pre-linguistic precursors (Adachi, 2014; Bulf et al., 2015; de Hevia et al., 2014; Drucker & Brannon, 2014; Lourenco & Longo, 2010; Rugani et al., 2014; Rugani et al., 2016; Vallortigara, 2017). However, results obtained with infants could be accounted for either by innate or acquired mechanisms. Recently it has been found that day-old neonates associate small quantities with the left space and large quantities with the right space, when controls for continuous physical variables are performed in the auditory domain (de Hevia et al., 2017). Our study extends those results addressing also the open question of the role of continuous physical cues in the visual domain. Up to now, a complete association between small numbers and left space and large numbers and right space has been provided solely in three-day-old domestic chicks (Rugani et al., 2015a). This evidence in inexperienced birds suggests that the role of reading and writing directionality is secondary in determining the orientation of the SNA (Brugger, 2015; Drucker & Brannon, 2014). However caution should be urged in the employment of animal models as a key to understanding the origin of the orientation of the human mental number line (Patro et al., 2016). Convergent evolution, namely the fact that species from diverse evolutionary lineages could independently develop similar features (Emery & Clayton, 2004), and differences in brain organization and lateralization (Drucker & Brannon, 2014; Fischer & Shaki, 2016; Vallortigara, 2017; Vallortigara & Versace, 2017) could affect the interpretation of comparative evidence (but see Rugani et al., 2015b; Rugani et al., 2016). Nevertheless, comparative as well as developmental studies have been unable, so far, to unequivocally address the origin of human mental number line. We overcame these limits by studying human newborns, a population characterized by a very limited visual experience.

Here we provide evidence for a complete, relative and magnitude-based spatial-numerical association in neonates. Hour-old newborns, initially habituated with a certain numerical value, spontaneously associated a smaller number with the left space and a larger number with the right space (Experiment 1). This association did not depend on the absolute magnitude of the number itself. Newborns habituated with number 4 associated the number 12 with the right (Experiment 2a), while newborns habituated with number 36 associated the number 12 with the left (Experiment 2b). This shows that SNA in newborns is relative.

Moreover, these findings could not be explained by continuous physical variables. In Experiment 2a and in Experiment 2b, we controlled for the overall perimeter, obtaining an inverse correlation between overall area and number. Had newborns associated space to overall area, instead of number, their choices would have been the opposite to what observed.

The fact that day-old newborns rely on numerical rather than on continuous quantitative information is in line with previous research highlighting that, at the start of postnatal experience, we spontaneously use abstract numerical cues (Izard *et al.,* 2009). In spite of some remaining criticisms (Leibovich & Ansari, 2016) number is considered a fundamental perceptual feature that our brain processes early in development to attain a complete representation of the external world (Anobile, Cicchini & Burr, 2016; Burr & Ross, 2008; Cicchini, Anobile & Burr, 2016; DeWind, Adams, Platt & Brannon, 2015; Fornaciai, Brannon, Woldorff & Park, 2017; Fornaciai, Cicchini & Burr, 2016; Park, DeWind, Woldorff & Brannon, 2016). Non-symbolic number sense is considered a developmental building block for the uniquely human capacity for mathematics (Carey, 2009; Dehaene, 2011; Spelke, 2000; Vallortigara, 2017). In support of this idea, it has been found that impairments to the non-symbolic numerical system are related to the occurrence of dyscalculia (Wilson & Dehaene, 2007). The acuity of the non-symbolic numerical system is predictive of mathematical ability in early childhood (Starr, Libertus & Brannon, 2013) and through training it improves proficiency in symbolic mathematics (Park & Brannon, 2013).

A correlation between the spatial representation of numbers and the level of mathematical skills has not been found in human adults (Cipora & Nuerk, 2013; Cipora et al., 2016). A possible explanation could be that professional mathematicians possess a more abstract and flexible numerical representation which reduces the left-to-right directionality of mental number line (Cipora et al., 2016). Moreover, it is still unclear if there is continuity between the SNA found in animals or preverbal children and the SNARC-like effects in processing symbolic numbers. Nevertheless, our data enlarge the range of influence of the non-symbolic numerical system on the symbolic one, showing that the former also affects the directionality of numerical spatial representation.

To the best of our knowledge, this is the first SNA demonstration in the visual domain in our species linked to minimal experience, supporting its biological origin. Our data confirm and extend de Hevia and colleagues' results (2017), supporting the hypothesis of a precocious association of numerousness and space both in auditory and in visual domain. This does not exclude that verbal (Shaki et al., 2009) and non-verbal (Bächtold, Baumüller & Brugger, 1998; Patro et al., 2016) experiences can modulate its original directionality. Even if the orientation of the mental number line reflects cultural effects (Shaki, 2009), its widespread presence across diverse cultures supports the idea that the association between number and space is a universal cognitive strategy (Göbel, Shaki & Fischer, 2011). The present evidence can be considered the starting point to disentangle the relative role and weight of cultural and neurobiological factors in determining the orientation of the human mental number line.

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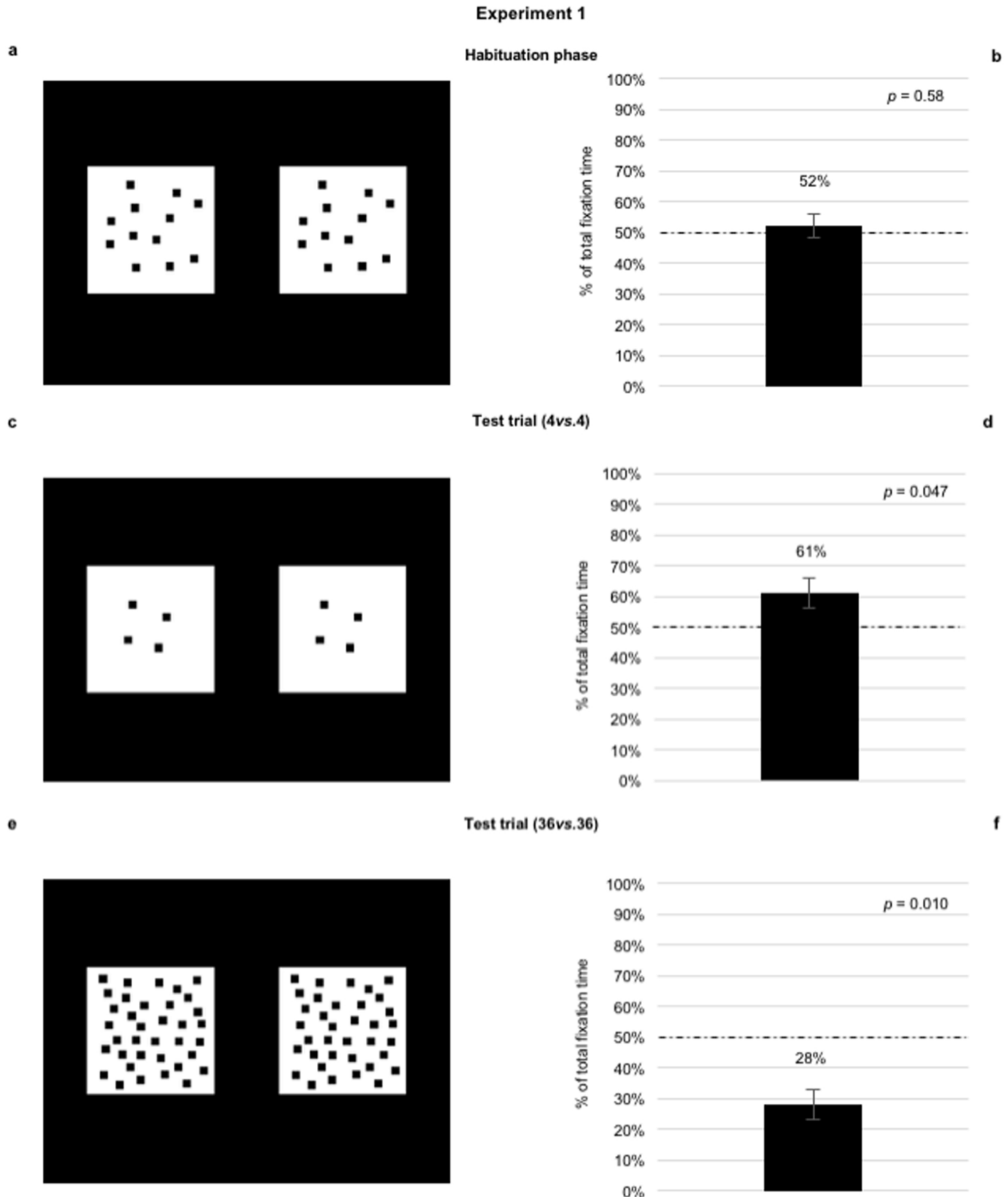

Figure 1. Stimuli and data on newborns' visual preference in Experiment 1.

Newborns were habituated with two identical stimuli, depicting 12 black squares of the same dimension (a). Once they had reached the habituation criterion, newborns underwent two test trials: one with a small number (4vs.4) (c), and the other with a large number (36vs.36) (e). During habituation, when the two stimuli depicted 12 squares, percentages of looking time toward the stimuli located on the left and on the right side of the screen did not significantly differ (b). In the test trial, when the two stimuli depicted 4 squares (4vs.4), newborns looked longer at the left-stimulus (d), when the stimuli depicted 36 squares (36vs.36), newborns looked longer at the right-stimulus (f). Error bars are standard error and dashed lines indicate chance level (50%). The percentage of total fixation time referred to the looking time for the left stimulus.

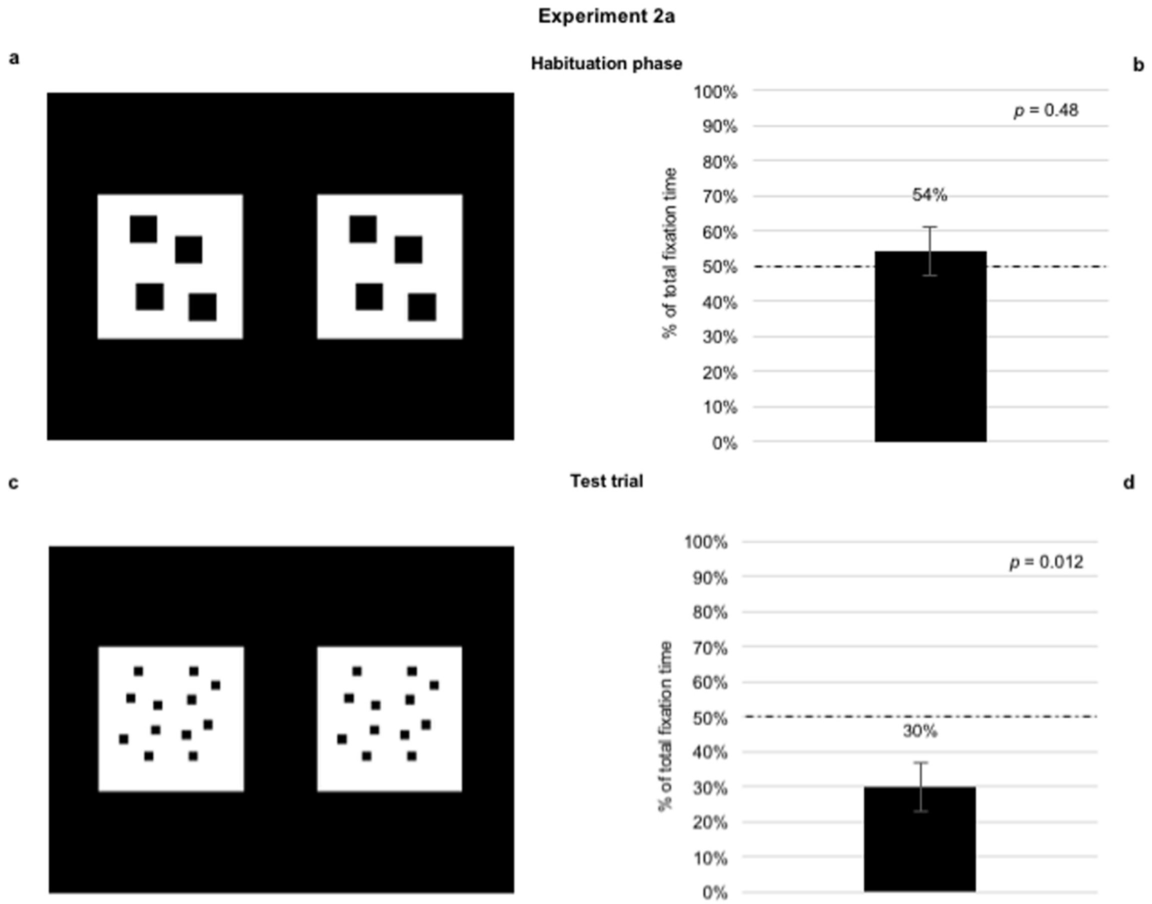

Figure 2. Stimuli and data on newborns’ visual preference in Experiment 2a.

In Experiment 2a we avoided the possibility that newborns used the overall perimeter (by equated it in all the stimuli) and the overall area (obtaining an inverse correlation between the number of squares and the overall area). We habituated a group of neonates with the number 4 (a) and then they were presented with the number 12 in the test trial (c). As for the habituation phase, percentages of looking time toward the left and right stimuli did not differ significantly (b). In the test trial, neonates looked longer at the right-stimulus (d). Error bars are standard error and dashed lines indicate chance level (50%). The percentage of total fixation time referred to the looking time for the left stimulus.

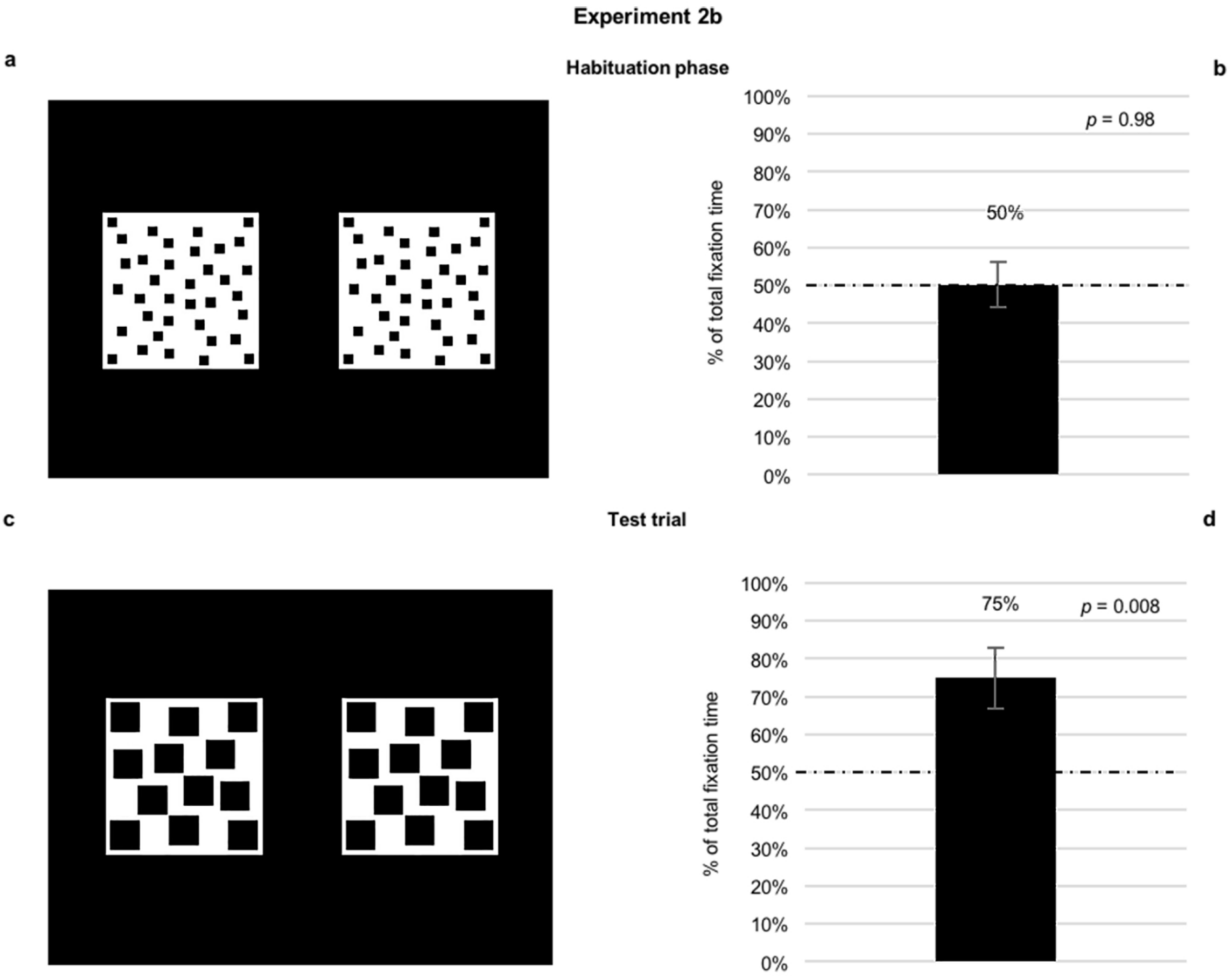

Figure 3. Stimuli and data on newborns' visual preference in Experiment 2b.

In Experiment 2b, as in Experiment 2a, we avoided the possibility that newborns used the overall perimeter (by equated it in all the stimuli) and the overall area (obtaining an inverse correlation between the number of squares and the overall area). We habituated a group of neonates with the number 36 (a) and then they were presented with the number 12 in the test trial (c). As for the habituation phase, percentages of looking time toward the left and right stimuli did not differ significantly (b). In the test trial, neonates looked longer at the stimulus on the left (d). Error bars are standard error and dashed lines indicate chance level (50%). The percentage of total fixation time referred to the looking time for the left stimulus.

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