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PAPER

Dissociation between small and large numerosities in newborn infants

Aurélie Coubart,[1,2] Véronique Izard,[1,2] Elizabeth S. Spelke,[3] Julien Marie[1,2] and Arlette Streri[1,2]

1. Université Paris Descartes, Sorbonne Paris Cité, France
2. CNRS UMR 8158, Laboratoire Psychologie de la Perception, Paris, France
3. Laboratory for Developmental Studies, Department of Psychology, Harvard University, USA

Abstract

In the first year of life, infants possess two cognitive systems encoding numerical information: one for processing the numerosity of sets of 4 or more items, and the second for tracking up to 3 objects in parallel. While a previous study showed the former system to be already present a few hours after birth, it is unknown whether the latter system is functional at this age. Here, we adapt the auditory-visual matching paradigm that previously revealed sensitivity to large numerosities to test sensitivity to numerosities spanning the range from 2 to 12. Across studies, newborns discriminated pairs of large numerosities in a 3:1 ratio, even when the smaller numerosity was 3 (3 vs. 9). In contrast, newborn infants failed to discriminate pairs including the numerosity 2, even at the same ratio (2 vs. 6). These findings mirror the dissociation that has been reported with older infants, albeit with a discontinuity situated between numerosities 2 and 3. Two alternative explanations are compatible with our results: either newborn infants have a separate system for processing small sets, and the capacity of this system is limited to 2 objects; or newborn infants possess only one system to represent numerosities, and this system either is not functional or is extremely imprecise when it is applied to small numerosities.

Introduction

Before their first birthday, infants can perceive the approximate number of items in sets of objects, and they can even engage in simple calculations such as ordering numerical quantities (Brannon, 2002; Picozzi, De Hevia, Girelli & Macchi Cassia, 2011), adding and subtracting (McCrink & Wynn, 2004; Wynn, 1992), or extracting ratios (McCrink & Wynn, 2007). To account for these findings, infants are thought to possess two cognitive systems encoding numerical information (Feigenson, Dehaene & Spelke, 2004; Hyde, 2011). First, the 'Approximate Number System' (ANS) encodes numerosities as internal magnitudes. Second, a system for tracking multiple objects in parallel (object files) supports representations of sets of up to 3 items. Although the conditions that trigger infants to process small sets using one or the other system are still largely unclear (Hyde, 2011; VanMarle & Wynn, 2009, vs. Lipton & Spelke, 2004), the idea of the existence of these two systems has received ample support, at least from the age of 10 months (Feigenson, Carey & Hauser, 2002a).

In infancy and throughout life, perception of large numerosities is approximate and is governed by Weber's law. For instance, 6-month-old infants discriminate arrays containing 8 vs. 16 or 16 vs. 32 dots when a host of parameters such as continuous extent, summed contour length, density, and area are controlled; but they fail to make a similar discrimination when the ratio between the two numerosities is closer to 1, such as 8 vs. 12 and 16 vs. 24 dots (Xu, 2003; Xu & Spelke, 2000; Xu, Spelke & Goddard, 2005). The critical ratio enabling discrimination (often referred to as 'the Weber ratio') gets progressively finer with age, especially during the first year of life. Whereas 6-month-old infants need a 1:2 ratio to discriminate numerosities successfully, neonates require a broader ratio (1:3; Izard, Sann, Spelke & Streri, 2009), and 9-month-old infants can discriminate numerosities at a finer ratio (2:3; Xu & Arriaga, 2007).

Address for correspondence: Aurelie Coubart, Laboratoire Psychologie de la Perception, UFR Biomédicale, 45 rue des Saints-Pères, 75006 Paris, France; e-mail: aurelie.coubart@gmail.com

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The precision of numerosity representations appears to be independent of the format of the stimuli presented to infants, children and adults. First, for infants, the Weber ratio is equivalent for stimuli as varied as arrays of dots or objects (Xu, 2003; Xu & Spelke, 2000; Xu *et al*., 2005), sequences of tones (Lipton & Spelke, 2004), or sequences of actions (Wood & Spelke 2005; see Feigenson *et al*., 2004; Feigenson, 2007). Second, infants are able to discriminate numerosities with a finer ratio difference when stimuli are redundant in two modalities (Jordan, Suanda & Brannon, 2008). Third and foremost, infants, children and adults are able to compare numerosities across stimuli presented in different formats and modalities (Barth, Kanwisher & Spelke, 2003; Barth, Lamont, Lipton & Spelke, 2005; Feigenson, 2011; Izard *et al.,* 2009), and a precise measurement of the acuity of numerical representations in adults showed no cost for switching modality (Barth *et al*., 2003).

In contrast, when tested with small numerosities, infants' behavior shows different signatures. First, in some tasks, behavior is not ruled by ratio but, instead, success is constrained by the size of the arrays. For example, Feigenson and Carey (2003) timed 12-month-old infants' searching behavior in a box, after seeing sets of one, two, three, or four objects introduced inside it. With a starting array of up to three objects, infants' searching behavior revealed that they knew when the box was empty or not. In contrast, infants failed to represent anything about the numerical content of the box for starting arrays of four objects.

As a second signature difference, in tasks testing discrimination between visual arrays, in the small number range infants tend to respond preferentially to aspects of stimuli such as the size or the density of the items, rather than their numerosity (Clearfield & Mix, 1999, 2001; Feigenson & Carey, 2005; Feigenson, Carey & Spelke, 2002b). This result contrasts with infants' performance with large arrays, showing sensitivity to numerosity with only limited responses to variations in other aspects of the displays (Brannon, Abbott & Lutz, 2004; Cordes & Brannon, 2009a).

Third, processing large and small numerosities leads to different neural signatures in 6-month-old infants as well as in adults (Hyde & Spelke, 2009, 2011). In a passive viewing task with small and large arrays of dots, infants and adults showed a neural signature modulated by the ratio between two subsequent numerosities in the large number range, but this signature was absent in the small number range. Conversely, infants showed a neural signature modulated by the absolute number of objects in the small number range. This signature was absent in the large number range: a double dissociation in the neural signatures of small and large number processing.

Lastly, further evidence for a separation between the small and large number systems lies in infants' failure to discriminate pairs of numerosities that cross the divide between small and large numerosities, when they are tested with ratios at the limit of their ability to discriminate large numerosities. For example, infants failed at discriminating a small (2) vs. a large (4) number of dots, despite the fact that pairs of large numerosities separated by a ratio of 2:1 are successfully discriminated at this age and in the same paradigm (Cordes & Brannon, 2009b; Xu, 2003). Impressively, infants still fail at this discrimination even when the ratio is more favorable (2 vs. 6) (Cordes & Brannon, 2009b). With pairs contrasting a small vs. a large numerosity, instead of a preference for the novel numerosity, Cordes and Brannon (2009b) found a preference for the larger numerosity, independently of the habituation condition. The failure to observe a preference for the novel numerosity, and the emergence of a preference for the larger numerosity create a behavioral double dissociation between processing numbers exclusively in the large number range and processing numbers that span the two ranges. Note, however, that infants did discriminate a large from a small numerosity when the ratio difference between the numerosities was doubled (2 vs. 8) (Cordes & Brannon, 2009b).

Here, we asked whether infants possess separate systems for encoding small and large numerosities as early as they can be tested, i.e. in the few first days following birth. In an earlier study, we showed that newborns possess an abstract, approximate representation of numerosities in the large number range (4 +), indicative of ANS representations, and that they use this representation to detect a numerical correspondence across modalities and formats (from auditory, temporal sequences to visual, spatial arrays). Do neonates possess a system of object tracking capable of encoding numeric information for small sets (1–3 objects), as do older infants? If so, does this system show dissociable properties from the system of large number representation?

Some studies provide evidence that infants discriminate between small numerosities (2 vs. 3) at birth, even for ratios finer than the 3:1 limit observed with large numerosities, but the interpretation of these results can be questioned. First, Antell and Keating (1983) tested newborns' ability to discriminate two dots from three dots; however, while they controlled for the distance between the dots or their density, they did not control for item size or total surface area, raising the possibility that these attributes drove the discrimination (see Clearfield & Mix, 1999, 2001, for evidence that older infants are sensitive to contour length and total surface area in visual arrays for sets of 2 or 3 items). Further, and most

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crucially, they used the two same patterns for each number in the familiarization and test phases, and therefore newborns could have simply recognized the configurations. A second study tested newborns' capacity to discriminate words of 2 vs. 3 syllables (Bijeljac-Babic, Bertoncini & Mehler, 1993). This study used stimuli of greater variability in the familiarization and test phases; however, words are a very specific stimulus for infants so it is not clear whether the success at this task is due to a general capacity to represent small numerosities, or if it reveals a mechanism specific to language for distinguishing words from one another. Third, recently Turati, Gava, Valenza and Girardi (2013) showed that newborn infants spontaneously prefer to look at images displaying 3 sets of objects over images with 2 sets. However, while the summed area was controlled between arrays, the arrays containing 3 sets occupied a larger surface than the arrays containing 2 dots. Thus, in this study it is not clear whether newborns responded to a numerical contrast between 2 and 3, rather than on the basis of occupied surface area – especially since the authors showed that newborns also preferred a stimulus with a greater occupied surface area, when the number of sets was controlled.

On the other hand, a brain imaging study performed with 3-month-old infants found no difference in the brain response to pairs of small (2 vs. 3) and large (4 vs. 8, 4 vs. 12) numerosities (Izard, Dehaene-Lambertz & Dehaene, 2008). For all pairs of numerosities, deviant numbers elicited a late negative response over parietal electrodes, similar in topography to the ratio-dependent response to large numbers observed by Hyde and Spelke (2011). The discrepancy between the results of these two studies may suggest that object file representations of sets of 2 and 3 objects emerge between 3 and 6 months of age; nonetheless, the analyses by Izard *et al.* were not designed to emphasize differences between conditions, and therefore, the absence of a difference in the brain response to small and large numerosities at 3 months should be taken with caution.

In the present study, we tested whether newborn infants possess a separate system to process small numerosities, just as older infants do. We designed five experiments, based on the methodology of Izard *et al.* (2009), and varying the numerosities presented to newborn infants. After being familiarized with sequences containing the same number of sounds, newborns viewed arrays of images on a computer screen, the auditory sequences still playing in the background. The number of images was either congruent or incongruent with the number of sounds that accompanied them. The use of such a bimodal matching paradigm avoids the possibility for newborns to succeed based only on purely auditory, linguistic, or visual capacities (contrary to Bijeljac-Babic *et al.*, 1993, and Antell & Keating, 1983). The first experiment was essentially a replication of one experiment by Izard *et al.* (testing discrimination of 4 vs. 12), albeit with a shorter familiarization time. In the second experiment, we used the same paradigm to test newborns' matching of two putatively small numerosities across modalities (2 vs. 3). Given that the newborns did not appear to match these two numerosities, in the next three experiments we used a different strategy and looked for infants' ability to compare small vs. large numerosities, while keeping the ratio between the numerosities constant. Experiments 3 and 4 tested matching for numerosities 2 and 6 using different controls on the non-numerical aspects of the stimuli. Newborn infants showed no evidence of matching these numerosities, in accord with the findings of studies of older infants (Cordes & Brannon, 2009b). In Experiment 5, therefore, we probed the status of the numerosity 3, by testing newborns with the pair 3 vs. 9.

General methods

Participants

A total of 80 healthy full-term newborns (33 girls) participated in these experiments (mean age: 54.15 h, range: 11.41 h–104.82 h, and range of weight: 2710 g–4510 g). All infants had an Apgar score of at least 9 after five minutes. Newborns whose mothers had major complications during pregnancy and those with medical problems were systematically excluded from the study. Infants were recruited directly inside the maternity unit, with the authorization of the director of the maternity unit and informed consent was obtained from a parent of each infant. Another 44 infants were brought to the testing room but failed to complete the experiment because they fell asleep (12) or cried (32). Finally, an additional 41 newborns were excluded after completion of the experiment because of video equipment failure (3), error in the program presenting stimuli (6), experimenter intervention (5), drowsiness (8), fussiness (2), or because offline recoding showed unclear looking behavior (16) or looking times at ceiling (1). This attrition rate is typical of newborn looking time studies (Izard *et al.*, 2009).

Stimuli

Stimuli were generated using the same parameters as in Izard *et al.* (2009). The sounds used for auditory stimuli were sequences of repeated syllables. The silence between

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two sequences varied randomly between 1 and 3 seconds. For each participant, all the sequences contained the same number of syllables. Participants were randomly assigned either to the larger or to the smaller numerosity for the auditory familiarization. The duration of individual syllables was longer in the familiarization to the small numerosity than in the familiarization to the large numerosity, such that the total duration of the sequences was the same for all the participants. Therefore, the participants familiarized to the smaller and the larger numerosity received the same amount of exposure to auditory numerosities. The visual stimuli were colored smiley faces of six different shapes (red square, pink circle, yellow triangle, green diamond, orange star and white heart). Unless stated otherwise, the individual size of the items was always the same (diameter from 2.8 to 4.8 cm), independently of the visual numerosity presented, so that the total area increased with numerosity. The smiley faces were animated with a stroboscopic movement as a group, not synchronous with the syllable repetitions. All elements were identical in each test trial, but changed between the four trials. The order of presentation of the different smiley images and their association with the small and the large numerosities was chosen at random for each participant.

Procedure

The experiment started with a 60 s familiarization phase, during which only the auditory sequences were played and the screen remained black. After the familiarization, four visual test trials were presented on the screen while the auditory accompaniment continued (Figure 1a). Auditory and visual stimuli were pre sented simultaneously in order to reduce memory load, while also potentially strengthening newborns' representation of numerosity (Jordan & Baker, 2011). Each test image remained on the screen until the baby had been looking for 1 minute or had stopped to look for 2 seconds.

Data recording and analysis

An experimenter, blind to the visual stimuli presented, coded the newborn's looking times online by pushing a button on the keyboard when the baby looked at the screen. A second coding of the looking times was conducted offline by one or two other experimenters (depending on the experiment), also blind to experimental conditions. In some cases, the offline coder judged that the video was not of sufficient quality to allow reliable judgments: these participants were excluded from the final sample. Because newborns' looks are not always easy to code (if the eyes are not wide open), and online coding was necessarily liberal so as not to end a trial prematurely (for example, if an infant sneezed, the experimenter did not stop the trial), a third coding was performed when the judgment of the offline coder differed from online coding by more than 5 seconds (30% of all trials). In two cases, the second offline recoding differed from both previous measurements by more than 5 s: these two infants were excluded from analyses. The analyses reported below are based on the average of the two most convergent[1] measurements for each trial (online coding and second offline coding: 18 trials; first and second offline coding: 74 trials).

Data were analyzed in an ANOVA with two between-subject factors of Familiarization (sequences presenting the smaller or larger number of sounds) and Order of test presentation (congruent first or incongruent first) and two within-subject factors of Test type (congruent or incongruent) and Test pair (first or second). When appropriate, in order to compare the results between experiments we also ran an ANOVA with three between-subject factors of Experiment, Familiarization (sequences presenting the smaller or larger number of sounds) and Order of test presentation (congruent first or incongruent first) and two within-subject factors of Test type (congruent or incongruent) and Test pair (first or second).

Experiment 1: Audio-visual matching of two large numerosities (4 vs. 12)

This first experiment was essentially a replication of Izard *et al.* (2009), except that we used a shorter familiarization period (60 s instead of 120 s). The reduction of the familiarization period was originally intended to reduce the attrition rate in participants.

Methods

The methods were identical to those described in the General Methods except as follows.

Participants

Sixteen healthy full-term newborns (five girls) were included in this experiment (mean age: 52.24 h, range: 16.12 h–99.2 h, and range of weight: 2730 g–4510 g).

[1] We obtained the same results with analyses based (1) only on the online coding; (2) only the first online coding; or (3) the average of the online coding with the first offline coding.

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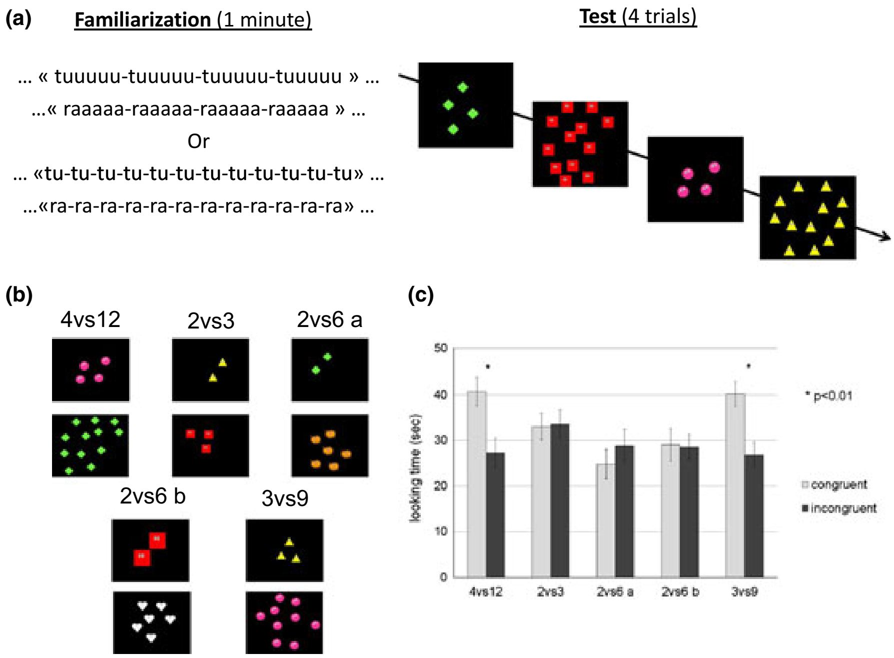

Figure 1 *Display and results for Experiments 1–5. (a) General procedure, illustrated here with numerosities 4 and 12: newborn infants were first familiarized to sequences of sounds for 60 s. Then they saw four visual test displays in sequence, containing either a congruent or an incongruent number of items. (b) Visual arrays presented to the infants in Experiments 1–3 (top row) and 4–5 (bottom row). (c) Results of Experiments 1–5 (left to right). Newborn infants looked longer at the visual arrays that were congruent in numerosity with the auditory sequences when presented with pairs of numerosities larger than 3 (4 vs. 12 and 3 vs. 9), but not when the contrast presented involved numerosity 2 (2 vs. 3, 2 vs. 6 a. and 2 vs. 6 b.). Error bars are standard error of the mean.*

Stimuli

Stimuli were generated according to the procedures described in the General Methods. Auditory sequences contained either 4 or 12 repeated syllables, for a total mean duration of 2.9 s per sequence. Visual arrays contained either 4 or 12 items (Figure 1b).

Analysis

Data were analyzed in a single ANOVA with two between-subject factors of Familiarization (sequences presenting 4 or 12 sounds) and Order of test presentation (congruent first or incongruent first) and two within-subject factors of Test type (congruent or incongruent) and Test pair (first or second).

Results and discussion

Results show a main effect of Test type ($F(1, 12) = 12.8$, $p = .004$): consistent with previous results (Izard *et al.*, 2009), infants looked longer at the congruent test trials (31.6 s) than at the incongruent trials (22.8 s) (13 of 16 infants looked longer at the congruent tests and 3 looked longer to the incongruent test trials, see Figure 1c). An interaction between Test pair and Test type was also observed ($F(1, 12) = 6.6$, $p = .024$), as the preference for the congruent trials was stronger in the first test pair (first test pair: congruent trial: 46.7 s, incongruent trial: 25.1 s; second test pair: congruent trial: 34.6 s, incongruent trial: 29.4 s). No other main effects or interactions were observed.

In summary, despite the shorter familiarization period, newborns readily detected the numerical correspondence between stimuli containing 4 or 12 items, replicating the findings in Izard *et al.*, 2009.

Experiment 2: Crossmodal matching of two small numerosities (2 vs. 3)

Even though older infants' discrimination of large numerosities is approximate and ratio-dependent, in the small number range infants can sometimes make exact discriminations amongst numerosities that are much closer in terms of ratio, such as 2 vs. 3. In Experiment 2, we examined whether the same pattern of behavior is

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present in newborns by adapting the previous paradigm to test the discrimination between 2 and 3. Since newborns are not able to discriminate large numerosities in ratios finer than 1:3, success in this condition would provide evidence for the existence of a separate system for small numerosities.

Method

The methods were identical to those described in the General Methods except as follows.

Participants

Sixteen healthy full-term newborns (six girls) were included in this experiment (mean age: 51.7 h, range: 19.9 h–91.6 h, and range of weight: 2860 g–3980 g).

Stimuli

Stimuli were generated according to the procedures described in the General Methods. Because the numerosities tested were smaller, auditory sequences were shorter on average (1.2 s). Visual arrays contained two or three items (Figure 1b).

Analyses

In addition to the main ANOVA, we ran a second ANOVA comparing Experiment 1 (large numerosities) to Experiment 2 (small numerosities). The latter ANOVA had three between-subject factors of Experiment (4 vs. 12 or 2 vs. 3), Familiarization (sequences presenting the smaller or larger number of sounds) and Order of test presentation (congruent first or incongruent first) and two within-subject factors of Test type (congruent or incongruent) and Test pair (first or second).

Results

The main ANOVA yielded no main effect or interaction (all ps > .2). Newborns looked equally at incongruent and congruent test trials (33.1 s vs. 33.5 s) (7 of 16 infants looked longer at the congruent test trials, 7 looked longer at the incongruent test trials and 2 showed no preference, see Figure 1c).

The ANOVA comparing Experiment 1(4 vs. 12) and Experiment 2 (2 vs. 3) revealed a significant effect of the Test type ($F(1, 24) = 5.1$, $p = .033$), together with an interaction between Experiment and Test type ($F(1, 24) = 5.9$, $p = .023$): newborn infants looked longer at the congruent test in Experiment 1(4 vs. 12), but not in Experiment 2 (2 vs. 3).

Discussion

Newborn infants failed to match numerosities 2 and 3 across the auditory and visual modalities. This result suggests that, contrary to older infants, newborns may not possess a separate system to represent small numerosities.

However, it is possible that our crossmodal matching paradigm is not appropriate for testing small numerosities. If object file representations do not yield a summary symbol of number, amodal representations of objects may play a crucial role in infants' ability to match small numerosities across modalities and formats. Note however that in our paradigm, infants were not provided with any cues indicating that the individual items in the auditory and visual modalities signal the same amodal objects. This contrasts with most previous studies of crossmodal matching with small numerosities, which either introduced a familiarization phase to teach object-based associations to infants (Kobayashi, Hiraki & Hasegawa, 2005), or capitalized on associations that were expectedly present in the infants' repertoire (Feron, Gentaz & Streri, 2006; Jordan & Brannon, 2006). More specifically, Kobayashi *et al.* (2005) started their study with a familiarization phase aimed at training infants to associate one sound with one visual object; Jordan and Brannon (2006) used talking faces and voices presented in synchrony, an association that can be recognized from birth (Guellaï, Coulon & Streri, 2011); and Feron *et al.* (2006) used tactile and visual stimuli with similar shape features. Only one earlier study had employed stimuli that did not present a natural pairing between the auditory and visual modalities (images of objects vs. drum beats) (Starkey, Spelke & Gelman, 1983); however, this study has not always been replicated (Mix, Levine & Huttenlocher, 1997; Moore, Benenson, Reznick, Peterson & Kagan, 1987). In our experiment as well, because the auditory and visual stimulations did not share any feature, infants may not have been inclined to represent the situation in terms of amodal objects, and therefore failed to detect the object correspondences.

Given this caveat, we elected to pursue a different strategy in testing further for a dissociation between the small and large number ranges at birth. The next three experiments test newborns with discriminations between a small and a large numerosity. Typically, older infants fail at these discriminations, even when the ratio is favorable with respect to their representation of large numerosities (Cordes & Brannon, 2009b). We therefore predicted that newborn infants would fail as well if they also possess separate systems to represent small and large numerosities. In contrast, if newborn infants have only one system that serves equally to represent all numerosities in the same approximate format, they should succeed at

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discriminating any pair of numerosities separated by a 3:1 ratio, including 2 vs. 6 or 3 vs. 9.

Experiment 3: Matching a small vs. a large numerosity (2 vs. 6)

To test the capacity of the approximate number system to represent all numerosities from small to large ranges at birth, we tested newborns on a discrimination between a small (2) and a large (6) numerosity. The two quantities chosen are in a 3:1 ratio, so they are distant enough to be discriminated within the system of approximate number representation.

Method

The methods were identical to those described in the General Methods except as follows.

Participants

Sixteen healthy full-term newborns (seven girls) were included in this experiment (mean age: 59.4 h, range: 11.4 h–96.8 h, and range of weight: 2710 g–3790 g).

Stimuli

Stimuli were generated according to the procedures described in the General Methods. The auditory stimuli were sequences of either two or six repeated syllables with a total mean duration of 1.4 s per sequence. Visual arrays contained either two or six items (Figure 1b).

Data analysis

In addition to the ANOVA analyzing Experiment 3 itself, we compared the results of the present experiment (small vs. large numerosity) with those of Experiment 1 (large numerosities) by means of a second ANOVA with the same factors as previously (see comparison of Experiments 1 and 2).

Results

Looking times showed a significant interaction between Familiarization condition and Test type ($F(1, 12) = 8.2$, $p = .014$). In general, all infants tended to look longer at the displays containing 6 objects, regardless of the condition of familiarization (familiarization with 6 sounds: test 6 m = 33.2 s; test 2: m = 25.0 s; familiarization with 2 sounds: test 6 m = 32.7 s, test 2: m = 16.5 s; 13 of 16 infants looked longer at the displays containing 6 items, 2 looked longer at the 2 items and 1 showed no preference, see Figure 1c). No other main effect or interactions were observed.

In order to assess these results with respect to the discrimination of large numerosities, the results of Experiment 3 were compared with those of Experiment 1. The preference for the larger numerosity was evident in this general ANOVA as well ($F(1, 24) = 7.1$, $p = .013$), as was the interaction between Test type and Test pair observed in Experiment 1 ($F(1, 24) = 5.4$, $p = .029$). More crucially, the difference in results across experiments yielded a significant interaction between Experiment and Test type ($F(1, 2\ 4) = 9.4$, $p = .005$). When contrasting a small numerosity (2) with a large numerosity (6), infants failed at matching these quantities across modalities, whereas they succeeded with two larger numerosities in the same ratio (4 vs. 12).

Discussion

Unlike the 4 vs. 12 experiment, in the 2 vs. 6 experiment newborns failed to match the sequences of sounds with visual arrays on the basis of numerosity. Instead, they looked longer at the images containing 6 items, regardless of the familiarization condition. Interestingly, older infants showed the same consistent behavior when tested with a pair of visual numerosities spanning the small and large ranges (Cordes & Brannon, 2009b); and newborns have been reported as looking preferentially at arrays that are more numerous and/or are of greater spatial extent (Turati *et al.*, 2013). Because continuous extents varied with numerosity in our experiment, however, we cannot be sure that the preference for the 6-item array was driven by numerosity. Regardless of the reason for infants' preference for the 6-item array, the observed dissociation across experiments nonetheless suggests that newborn infants do not process the numerosity 2 in the same way as larger numerosities.

It is possible that newborns failed to look at the stimuli with 2 objects just because this display was too small to attract their attention. Remember that in Experiments 1–3, the size of individual items was matched across numerosities, such that the summed area was actually smaller for the smaller numerosity. In order to address this question, we ran a second experiment with the number pair 2 vs. 6, equating the summed area between displays containing either 2 or 6 images.

Experiment 4: Matching a small vs. a large numerosity with summed area equated

To test the possibility that newborns have failed at Experiment 3 because the 2-item arrays were too small to

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attract their attention, we ran a control experiment where cumulated area was equated across images with 2 or 6 items.

Method

The methods were identical to those described in the General Methods except as follows.

Participants

Sixteen healthy full-term newborns (eight girls) were included in this experiment (mean age: 57.4 h, range: 25.1 h–93.3 h, and range of weight: 2840 g–4290 g).

Stimuli

The auditory stimuli were the same as in Experiment 3. The visual stimuli differed from previous ones in the way individual item size was controlled. The size of each shape was controlled so that the cumulated area was always the same, independently of the number of items presented. Thus, in test images with two items, individual sizes were 3 times bigger in terms of area than in 6-item images (Figure 1b).

Data recording and analysis

Data were first analyzed in a single ANOVA focused on Experiment 4. Next, the results of Experiments 3 and 4 were compared in a general ANOVA using the same factors as previously.

Results

Looking times revealed an interaction between Familiarization and Test type that approached significance ($F(1, 12) = 4.6$, $p = .053$): again, infants tended to look longer at the test containing 6 items (33.6 s) than at the test containing 2 items (23.9 s) (11 of 16 infants looked longer at the displays containing 6 items, 4 looked longer at the 2 items and 1 showed no preference, see Figure 1c). Moreover, in Experiment 4 a main effect of Familiarization was observed ($F(1, 12) = 6.6$, $p = .025$), as infants looked longer when familiarized with sequences containing 6 sounds (33.3 s) than when familiarized with sequences of 2 sounds (24.3 s). No other effects or interactions were observed.

Experiments 3 and 4 were compared directly using a general ANOVA. This analysis yielded no effect or interaction involving the factor Experiment, in line with the finding that the behavior did not differ across these two experiments. The pooled ANOVA replicated the effects obtained in separate experiments: a main effect of Familiarization ($F(1, 24) = 5.2$, $p = .032$), and an interaction between Familiarization and Test type ($F(1, 24) = 11.5$, $p = .002$).

Discussion

Again, despite the fact that we presented two items with the same cumulative area as the six items, newborns failed to match the numerosities 2 and 6 across the visual and auditory modalities. Thus, the absence of matching cannot be explained by a failure to see the two small items. Rather, newborns show the same pattern of results as older infants, failing to respond to a contrast between a large vs. a small numerosity, in a situation where they had successfully discriminated between two large numerosities.

In both Experiments 3 and 4, infants showed a looking preference for the 6-item array. In Experiment 4 the preference for the 6-item array cannot be attributed to its greater cumulative surface area, because that variable was controlled. This preference might be due to other stimulus variables, since variables such as contour length varied with numerosity in the present study. Nevertheless, contour length differences also distinguished the visual arrays used in the previous experiments (Izard *et al.*, 2009; Experiments 1 and 2), where it induced no such preference. It is possible that the results of Experiments 3 and 4 are driven by representations of numerosity: newborn infants may have an intrinsic preference for arrays with large numbers of elements over arrays of 1–2 elements, in line with Turati *et al.*'s (2013) findings. Further testing is needed to decide between these alternatives.

In older infants, the limit between the small and large number ranges lies between 3 and 4. In the next experiment, we aimed to determine whether this limit is the same in newborn infants, by testing infants with the pair 3 vs. 9. If the object tracking system has a limit of 3 for newborn infants, then infants should fail at matching these numerosities across senses, as they did in Experiments 3 and 4, because this discrimination task would straddle the boundary between the two systems. In contrast, if the object tracking system has a limit of 2 for newborn infants, then infants should succeed, as they did in Experiment 1.

Experiment 5: Matching numerosities 3 vs. 9

Using the same paradigm as before, we tested infants with the pair 3 vs. 9 to see whether the newborns' behavior would pattern as with the pair 2 vs. 6

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(preference for the larger visual numerosity, independently of the auditory stimulation) or as with 4 vs. 12 (preference for the congruent numerosity).

Method

The methods were identical to those described in the General Methods except as follows.

Participants

Sixteen healthy full-term newborns (seven girls) were included in this experiment (mean age: 50.1 h, range: 17.5 h–104.8 h, and range of weight: 2770 g–3820 g).

Stimuli

Stimuli were generated according to the procedures described in the General Methods. Auditory stimuli were sequences of either 3 or 9 repeated syllables with a total mean duration of 2.1 s. per sequence. Visual arrays contained either 3 or 9 items (Figure 1b).

Data analysis

Data were first analysed in an ANOVA restricted to Experiment 5. Next, in order to test whether the pair 3 vs. 9 patterned with the pair 2 vs. 6 or with the pair 4 vs. 12, we ran two other ANOVAs, using the same factors as previously.

Results

Results showed a main effect of Test type ($F(1, 12) = 16.9$, $p = .001$): infants looked longer at the congruent trials (40.2 s) than at the incongruent trials (26.8 s) (15 of 16 infants looked longer at the congruent tests and 1 looked longer at the incongruent test trials, see Figure 1c). No other main effects or interactions were observed ($p > .1$).

The ANOVA comparing performance in the 4 vs. 12 and the 3 vs. 9 experiments showed no effect or interaction with the factor Experiment ($p > .07$). This analysis revealed a main effect of Test type ($F(1, 24) = 29.1$, $p < .0001$): infants looked longer at the congruent trials. Besides these main effects, the preference for the congruent numerosity was stronger in the first pair of trials than in the second pair, resulting in a significant interaction between Test type and Test pair ($F(1, 24) = 4.4$, $p = .046$).

In contrast, the ANOVA comparing the 2 vs. 6 a and 3 vs. 9 experiments revealed a significant interaction between Experiment and Test type ($F(1, 24) = 10.5$, $p = .003$). Besides, this pooled analysis showed that in general, infants looked longer at the more numerous displays as indicated by an interaction between Familiarization and Test type ($F(1, 24) = 9.2$, $p = .006$).

Discussion

Newborns behave with numerosities 3 and 9 in the same way as they did with numerosities 4 and 12, matching the auditory numerosities with the visual numerosities. These results contrast with the pair 2 vs. 6, where no such matching was observed and infants instead showed a preference for the more numerous arrays. This behavior was observed even despite newborns' general preference for the most numerous displays, as suggested by the analyses that combined data across Experiments 5 and 3.

These findings provide evidence that at birth, the limit between the small and large ranges of numerosities is situated between 2 and 3. In this respect, newborn infants contrast with older infants whose behavior changes between numerosities 3 and 4.

General discussion

In five experiments, we used a matching task between auditory sequences and visual arrays to compare encoding of small and large numerosities in newborn infants. Our first finding replicated previous findings, in that infants were able to match stimuli on the basis of numerosity for a pair of large numerosities separated by a 3:1 ratio (4 vs. 12). Next, we tested whether newborns would show the same response for a contrast between two small numerosities, even for a ratio that is finer than 3:1 (2 vs. 3). However, newborns failed in this condition, thus failing to provide any evidence for a separate system for small numerosities. In the next two experiments, we chose an alternative strategy to seek evidence for a dissociation between large and small numerosities at birth, by testing pairs contrasting a small vs. a large numerosity, while keeping the ratio between numerosities at 3:1. This time, we observed the same dissociation as in older infants: Using the smallest tested ratio at which they successfully discriminate between a pair of large numerosities (3:1), newborn participants failed to match a small (2) vs. a large (6) numerosity. Instead they showed the signature of discrimination across boundary between large and small numerosities: a preference for the large number array. Lastly, building on this dissociation, we tested where the limit between small and large numerosities would fall at birth, using an intermediate pair of numerosities (3 vs. 9). Unlike in older infants, for newborns numerosity 3 patterned like numerosity 4,

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rather than like numerosity 2: Newborn infants successfully matched 3 vs. 9 items across the visual and auditory modalities, just as they succeeded for 4 vs. 12.

Just like older infants, therefore, newborns show a behavioral double dissociation between small and large numerosities. Nevertheless, the border between small and large numerosities appears to change during the first year of life, falling between 2 and 3 at birth but between 3 and 4 for older infants. The presence of a border between 2 and 3 could explain newborn infants' failure to discriminate arrays of 2 vs. 3 objects in our Experiment 2.

The observed behavioral dissociations in infant's responses to numerical differences in the small and large number ranges in newborns and older infants is compatible with two alternative hypotheses. First, infants may have encoded all numerosities in terms of the Approximate Number System (ANS), but this system may not be operational or may be unreliable for very small numerosities. Indeed, if the computations underlying extraction of numerosity in the ANS rely on some summary statistics on stimuli (for example if the perception of numerosity is based on estimates of density and area; Dakin, Tibber, Greenwood, Kingdom & Morgan, 2011; Gebius & Reynvoet, 2012; Hollingsworth, Simmons, Coates & Cross, 1991; Hurewitz, Gelman & Schnitzer, 2006), these estimates may not be reliable for small numerosities, as it is hard to define summary statistics such as density for very small arrays. If that hypothesis is correct, because numerosity perception presents the same characteristic signatures throughout lifetime, the drop in precision between large and small numbers should be visible into adulthood as well.

In adults, ANS representations are operational in the small numerosity range (Burr, Anobile & Turi, 2011; Burr, Turi & Anobile, 2010; Hyde & Wood, 2011); however, because the small numerosities are so distant from each other in terms of ratio, it is difficult to assess the acuity of adults' ANS representations for small numerosities with sufficient precision to compare them with representations of large numerosities. Nevertheless, two observations are in line with the hypothesis of poorer ANS precision in the small numerosity range. First, focusing on large numerosities, several psychophysical studies found that in adults the Weber fraction is not strictly constant, but decreases progressively towards larger numerosities (Burgess & Barlow, 1983, range 10–400; Krueger, 1984, range 25–200; Newman, 1974, range 20–100). Second, even though infants fail at discriminating a small vs. a large numerosity for ratios that yield success with pairs of large numerosities, they eventually succeed when the ratio between the large and the small numerosities is doubled (2 vs. 8 or 1 vs. 4; Cordes & Brannon, 2009b). This finding suggests that infants may have access to ANS representations for numerosities 2 and 1, and also that these representations are noisier than the representations of larger numerosities. Further experiments should test whether the same is true of newborn infants, using for example a contrast of 2 vs. 12.

Alternatively, newborns and older infants may possess two different systems of numerical representations, such that large arrays are processed via the ANS, but small arrays preferentially elicit representations in terms of object files (Hyde, 2011). In the case of newborns, however, given our positive findings on the pair 3 vs. 9, parallel tracking would be limited to two objects, rather than three as in older infants (Feron *et al.*, 2006; Kobayashi *et al.*, 2005; Jordan & Brannon, 2006). Under this hypothesis, the failure to match a small vs. a large numerosity would stem from the difficulty of comparing across two different types of representations. This hypothesis is not incompatible with the previous one: Perhaps infants can represent small numerosities via the ANS system as well, but these representations are noisier than for larger numerosities, and are also less salient than object file representations.

Interpreting our findings in terms of the limit of the object file system implies that the capacity of the system develops over the first year of life, from two slots at birth to three slots by the age of 5 months (Feron *et al.*, 2006). In other experiments as well, the capacity of working memory has been shown to increase in the first year of life (Oakes, Hurley, Ross-Sheehy & Luck, 2011; Oakes, Ross-Sheehy & Luck, 2006; Ross-Sheehy, Oakes & Luck, 2003). In these experiments, infants were presented with two streams of briefly presented visual arrays: in one stream the same array was repeated constantly, while in the other, a change was introduced at each image, with one item changing either color (Ross-Sheehy *et al.*, 2003) or location (Oakes *et al.*, 2011). The same number of items was presented in the fixed or in the changing stream, and infants were tested for their preference using different numbers of items. If infants detect a change across arrays in one of the sequences, they should prefer to look at this more interesting display. Under these conditions, 7-month-old infants succeeded at the task for one, two and three items whereas 6-month-old infants looked longer to the changing stream only when the arrays contained one item.

Why would the capacity be limited to one object at 6 months under these conditions, whereas newborns appeared able to track two objects in our experiments, and generally, infants as young as 5 months can track up to three objects (Feron *et al.*, 2006)? Perhaps the pace of the presentation makes the working memory task more difficult; but also, memory resources may be taxed by the need to encode information about the identity or the

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location of the items – just as in adults, the measured capacity of VSTM is reduced for objects of increased complexity (Alvarez & Cavanagh, 2004).

In conclusion, we tested newborn infants' ability to discriminate across pairs of numbers in different ranges, and observed the same failure to discriminate a small vs. a large numerosity as in older infants. While our results provide suggestive evidence for the existence of separate systems dedicated to small and large numerosities at birth, the evidence that we present is only indirect. Further studies should be undertaken to seek positive evidence for the discrimination between two small numerosities (1 vs. 2). Such studies would bring definitive evidence for the existence of a system dedicated to small numerosities, devoid of the ratio signature of the large numerosity system and showing instead the set size signature of parallel representations of objects.

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