Representations of space, time, and number in neonates

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A rich concept of magnitude—in its numerical, spatial, and temporal forms—is a central foundation of mathematics, science, and technology, but the origins and developmental relations among the abstract concepts of number, space, and time are debated. Are the representations of these dimensions and their links tuned by extensive experience, or are they readily available from birth? Here, we show that, at the beginning of postnatal life, 0- to 3-d-old neonates reacted to a simultaneous increase (or decrease) in spatial extent and in duration or numerical quantity, but they did not react when the magnitudes varied in opposite directions. The findings provide evidence that representations of space, time, and number are systematically interrelated at the start of postnatal life, before acquisition of language and cultural metaphors, and before extensive experience with the natural correlations between these dimensions.

cognitive | development | numerical cognition

The origins of the abstract concepts of space, time, and number are longstanding topics of study, from the dawn of philosophy (1) and experimental psychology (2) to classical developmental psychology (3) and modern cognitive science (4–6). Kant (7) argued that representations of number, space, and time provide “a priori” intuitions and concepts that precede and structure all experience. Modern cognitive science provides methods to test these ideas experimentally. We now know that human newborns, and even inexperienced animals such as newly hatched chicks, are able to discriminate objects on the basis of numerosity a few hours after the start of postnatal experience (8, 9). When human newborns are presented with auditory sequences of syllables and visual arrays of objects, they look longer at the arrays that correspond to the auditory sequences in number than at arrays differing in number by a 1:3 ratio (8, 10). At birth, humans thus possess representations of approximate numerosity that are abstract enough to enable a generalization across stimuli as varied as sequences of syllables and sets of visual objects. Are newborn human infants able to perform further, yet more abstract, generalizations across different types of magnitudes?

Humans draw links between the dimensions of space, time and number, as shown by the presence of “number lines” (11, 12) and the use of spatial language to refer to time (13). Human adults link these dimensions automatically. When processing spatial and temporal, or spatial and numerical information simultaneously, representations of time and number are both affected by the spatial dimension (14, 15). The propensity to represent numerical magnitudes by the lengths of line segments (number lines) is a widespread phenomenon not only across cultures and species but also over human development. Human infants (16, 17), children (18, 19), educated human adults (18, 20), and uneducated adults living in remote cultures (11) map numbers onto corresponding line lengths. Similarly, spatial–temporal mappings show the universal effects of one of these dimensions on the other, both in human adults (14) and in adult monkeys (21). For instance, during the first year of life, 8- and 9-mo-old infants spontaneously create number-length mappings, such that greater numbers (e.g., array of dots) are related to longer line lengths (16), as well as time-length mappings, where larger temporal durations are associated to larger spatial extents (22).

Nevertheless, the links between the representations of space, time, and number could be formed by experience. Even though number-space mappings have been observed in remote cultures without formal instruction in mathematics or measurement devices, as well as in 8-mo-old human infants, it is possible that infants learn to link these dimensions to one another during the first months of postnatal life by observing the correlations between these variables that are naturally present in the environment. For example, visible arrays containing a greater number of objects tend to occupy larger regions of space, and auditory sequences containing a greater number of events tend to continue for a longer duration. Later in life, and across development, these associations might be strengthened and deepened by linguistic and cultural exposure. Alternatively, the human mind may be predisposed to relate these three fundamental dimensions before extensive experience with the natural correlations between numbers of objects, spatial extents, and temporal durations. Studies of human neonates, conducted near the beginning of their encounters with the external environment, and therefore with minimal exposure to these natural correlations, serve to distinguish between these possibilities. We tested 7- to 94-h-old neonates' sensitivity to pairings between aurally presented nonsymbolic numerosities and/or temporal sequences and visually presented horizontal line lengths.

Significance

Space, time, and number are connected in the world and in the human mind. How do these connections arise? Do we learn to link larger numbers and durations to longer spatial extents because they are correlated in the world, or is the human mind built to capture these relations? We showed that neonates relate both number and duration to spatial length when these dimensions vary in the same direction (number or duration increases as length increases), but not in opposite directions (number or duration increases and length decreases). After being familiarized to a pairing between two magnitudes, newborns expect these dimensions to change in the same direction. At birth, humans are sensitive to the common structure of these fundamental magnitudes.

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Results

Number and Time Mapped onto Spatial Length. In experiment 1, each infant was familiarized with a single visual line (either short or long) paired with a single auditory numerosity (sequences of either 6 or 18 syllables). After 60 s, all infants were presented with new movies (test phase) that implied either an increase (i.e., from 6 to 18) or a decrease (i.e., from 18 to 6) in auditory numerosity relative to the familiarization phase. In two consecutive trials, this new auditory sequence was paired with each of the two line lengths (the familiar and the novel one), resulting in one trial where only the auditory information changed and one trial where both the auditory and the visual information changed. Critically, depending on the familiarization condition, when both the auditory numerosity and visual length changed at test, they either changed in the same direction (either both increasing or both decreasing) or in opposite directions (one increasing, the other decreasing) (Figs. 1 and 2).

If newborn infants are sensitive to the common structure of different types of magnitude, they should react differently when the changes in the two dimensions are in the same direction, compared with two changes in opposite directions. Consistent with this prediction, we observed a significant interaction between familiarization condition and test [$F(1,30) = 4.7$, $P < 0.05$] (Fig. 3). When the changes in numerosity and length from familiarization to test were in the same direction, newborns looked longer at the new line length ($M = 45.9$ s) than at the familiar one [$M = 19.7$ s; $F(1,14) = 25.35$, $P < 0.001$]. This preference was observed both for infants who experienced an increase [$M = 42.1$ s vs. 19.9 s; $t(7) = 2.47$, $P = 0.04$, paired t test] and for those who experienced a decrease in number [$M = 49.9$ s vs. 19.5 s; $t(7) = 5.71$, $P < 0.001$, paired t test]. In contrast, infants who experienced opposite changes in numerosity and length from familiarization to test looked equally long at the two line lengths at test ($M = 31.6$ vs. 26.4 s; $F < 1$, $P = 0.54$). (Fifteen out of 16 infants who experienced magnitude changes at test in the same direction looked longer at the test trial presenting both the auditory and the visual changes [binomial test, $P = 0.001$; $Z = 3.21$, $P = 0.001$, Wilcoxon signed-rank test] whereas only 10 out of 16 infants who experienced the magnitude changes at test in opposite directions looked longer at the test trial presenting both the auditory and visual changes [binomial test, $P = 0.45$; $Z < 1$, $P = 0.44$, Wilcoxon signed-rank test; the two proportions differed marginally, $\chi^2(1) = 2.9$, $P = 0.08$].) Despite this difference in looking behavior at test, infants who experienced magnitude changes in the same direction at test were equally attentive during familiarization as infants who experienced magnitude changes at test in opposite directions [$t(30) = 1.3$, $P = 0.21$, unpaired t test]. Therefore, newborn infants mapped the numerical information contained in the auditory sequences to a visual spatial extent, and they expected the new auditory–visual pairing at test to implement magnitude changes in the same direction. However, because the syllable sequences were distinguished both by numerosity and by duration, infants may have mapped the auditory sequences to the line lengths using numerical cues, temporal cues, or both.

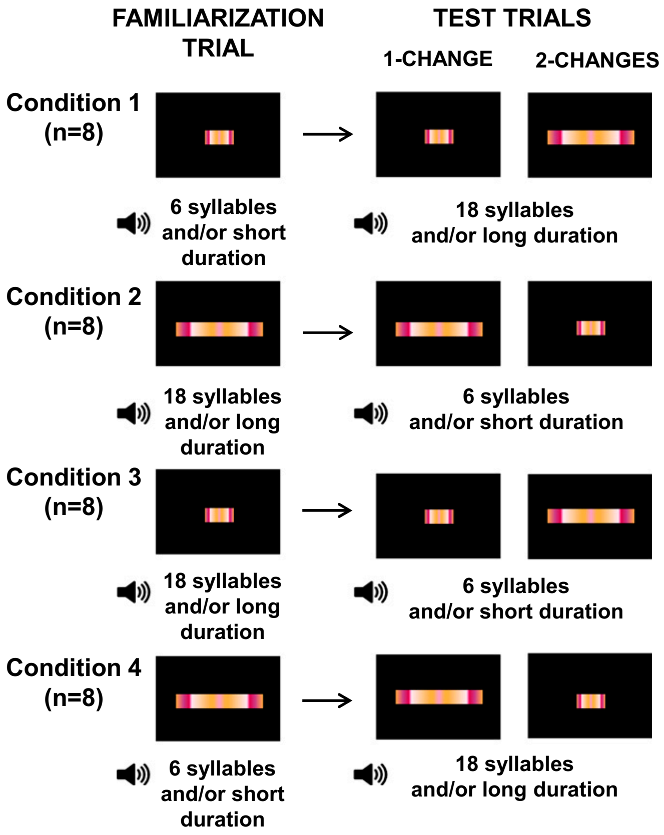

Fig. 1. Displays presented to newborns during the familiarization trial, the one-change test trial, and the two-change test trial. Each infant received only one of the four types of familiarization and test trials (conditions 1, 2, 3, 4). Infants familiarized with a 6-syllable and/or short-duration sequence paired with a short line, as well as infants familiarized with an 18-syllable and/or long-duration sequence paired with a long line, experienced two-change test trials where both dimensions changed in the same direction (conditions 1 and 2). Infants familiarized with a 6-syllable and/or short-duration sequence paired with a long line, as well as infants familiarized with an 18-syllable and/or long-duration sequence paired with a short line, experienced two-change test trials where both dimensions changed in opposite directions (conditions 3 and 4).

Number Mapped onto Spatial Length. In experiment 2, a new group of 32 infants were presented with 6- and 18-syllable sequences of equal temporal duration. This was achieved by lengthening the individual sounds in the 6-syllable sequence from experiment 1. The structure of the experiment was otherwise identical to experiment 1. All infants were presented with the same test trials, testing for generalization to a short and a long line after a change in numerosity. As in experiment 1, we observed a significant interaction between familiarization condition and test [$F(1,30) = 6.54$, $P = 0.01$] (Fig. 3). Infants who experienced concordant changes in numerosity and length from familiarization to test (i.e., both dimensions increasing or decreasing) looked longer at the test display containing the novel length [$M = 37.9$ s vs. 22 s; $F(1,14) = 9.89$, $P < 0.01$]. This preference was observed for infants who experienced an increase [$M = 37.9$ s vs. 21.3 s; $t(7) = 2.8$, $P = 0.02$, paired t test], and marginally for those who experienced a decrease in number [$M = 37.8$ s vs. 22.7 s; $t(7) = 1.85$, $P = 0.1$, paired t test]. [An ANOVA considering the variable increasing vs. decreasing showed no significant main effect ($F < 1$, $P = 0.5$) nor interactions (all Fs$(1,28) < 1.4$, all Ps > 0.25) involving this variable.] In contrast, infants who experienced opposite changes in numerosity and length from familiarization to test showed no differential looking at the two test displays ($M = 32.5$ s vs. 35.3 s; $F < 1$, $P > 0.6$) even though, in this group, the duration of individual syllables and the line length changed concordantly. This finding suggests that newborns were attending to the overall numerosity of the sequences, as in previous research (8, 10). (Fifteen out of 16 infants who experienced magnitude changes at test in the same direction looked longer at the test trial presenting both the auditory and the visual changes [binomial test, $P = 0.001$; $Z = 2.84$, $P = 0.004$, Wilcoxon signed-rank test] whereas only 7 out of 16 infants who experienced magnitude changes at test in opposite directions looked longer at the test trial showing both auditory and visual changes [binomial test, $P = 0.8$; $Z < 1$, $P = 0.7$, Wilcoxon signed-rank test; the two

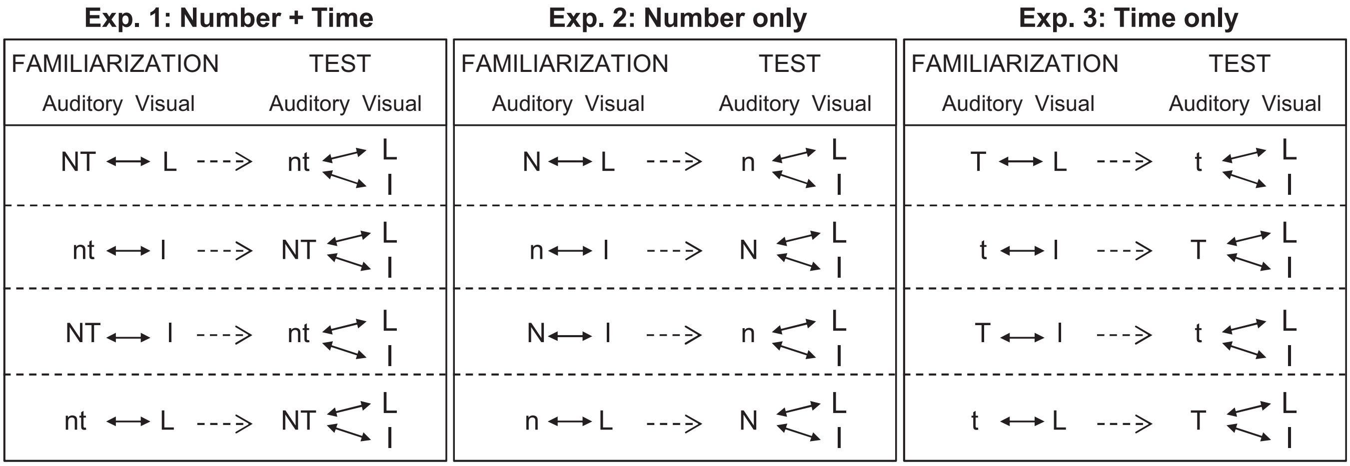

Fig. 2. Schematic representation of the magnitudes used in the familiarization and test phases for the three experiments (experiment 1, numerical and temporal cues; experiment 2, numerical cues only; experiment 3, temporal cues only). NT, large numerosity/long duration; nt, small numerosity/short duration; N, large numerosity; n, small numerosity; T, long duration; t, small duration; L, long length; l, short length.

proportions were significantly different, $\chi^2(1) = 7.1$, $P < 0.01$].) Again, looking times during the familiarization phase for infants who experienced the changes at test in the same direction were similar to those of infants who experienced the changes at test in opposite directions [$t(30) = -1.28$, $P = 0.21$, unpaired t test], suggesting equal attention to the displays in the two conditions. Together, experiments 1 and 2 provide evidence that neonates relate number to length both when relative numerosity correlates with duration and when it does not. Interestingly, newborns did not form expectations of congruency between line length and individual sound duration, perhaps because variations in sound duration across sequences tuned them to disregard this parameter (23) or because, just like older infants, they privilege numerosity over properties of individual elements in sets (24).

Time Mapped onto Spatial Length. Experiment 3 tested, in a new group of 32 neonates, for a linkage of duration to length in the absence of numerical changes. Instead of sequences of syllables differing in number, all of the infants were presented with 2 syllables separated by a continuous short or long tone, which matched in duration the 6- and 18-syllable sequences of experiment 1; the methods were otherwise identical to those in experiments 1 and 2. All of the infants were presented with two test events involving the novel auditory duration paired with the line of either the familiar or the novel length. Again, there was a significant interaction between familiarization condition and test [$F(1,30) = 12.27$, $P = 0.001$] (Fig. 3). The group of infants who experienced a concordant change in duration and length from familiarization to test looked significantly longer at the test display presenting the novel line length [M = 41.7 s vs. M = 21.3 s; $F(1,14) = 20.97$, $P < 0.001$]. This preference was observed both for infants who experienced an increase [M = 46.8 s vs. 19.9 s; $t(7) = 3.36$, $P = 0.01$, paired t test] and for those who experienced a decrease in duration [M = 36.7 s vs. 22.8 s; $t(7) = 3.56$, $P < 0.01$, paired t test]. In contrast, the group of infants who experienced the magnitude changes in opposite directions showed no systematic looking preferences at test [M = 32.1 s vs. 39.1 s; $F(1,14) = 1.15$, $P > 0.3$]. (Fourteen out of 16 infants who experienced changes at test in the same direction looked longer at the test trial presenting both the auditory and the visual changes [$P = 0.005$; Z = 3.21, $P = 0.001$, Wilcoxon singed-rank test] whereas only 5 out of 16 infants who experienced changes at test in opposite directions looked longer at the test trial showing both auditory and visual changes [binomial test, $P = 0.2$; Z = 1.29, $P = 0.2$, Wilcoxon signed-ranked test; the two proportions were significantly different, $\chi^2(1) = 8.3$, $P < 0.01$].) Despite these differences at test, infants who experienced changes at test in the same direction looked equally long at the familiarization displays as infants who experienced the changes at test in opposite directions [$t(30) < 1$, $P = 0.59$, unpaired t test]. Therefore, in the absence of

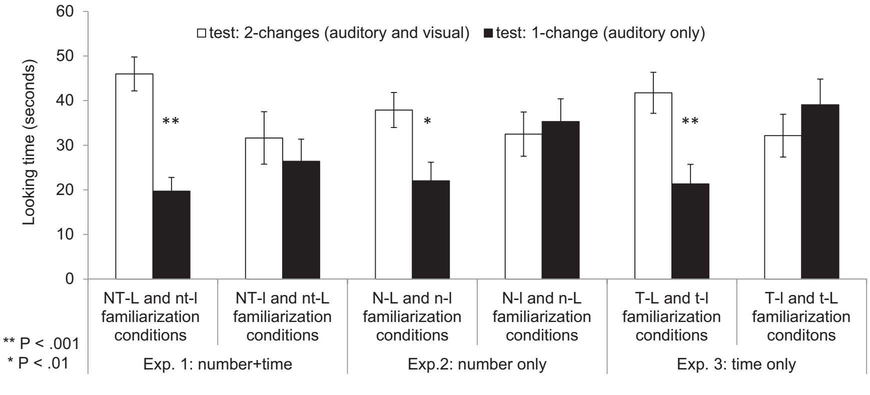

Fig. 3. Mean looking times (s) for the test trials. The test trials presenting two changes (both auditory and visual) vs. one change (auditory only) were significantly different only for infants who experienced a congruent change in magnitude across dimensions from familiarization to test, but not for those who experienced the magnitude change in opposite directions. Error bars correspond to the SEM.

numerical cues, newborn infants spontaneously linked auditory events of longer duration to visual lines of greater length.

Discussion

Previous research showed that humans at birth can learn arbitrary visual–auditory pairings: after being familiarized with one pairing, newborns recover attention when presented with a novel pairing compared with the familiar one (25). Our findings go beyond these early results because, instead of testing newborns' preference against the learned association, we presented them with two novel pairings at test and assessed their ability to generalize the information presented during familiarization to the new values of magnitude presented during test. To succeed in our tests, newborns had to build an expectation of congruency between magnitude-related changes in number, time, and space, from familiarization to test. Notably, neonates revealed this sensitivity both when numerical and temporal cues were simultaneously available (in experiment 1) and when number or duration was presented in isolation (respectively, in experiments 2 and 3). The human mind thus may be predisposed to relate these three fundamental dimensions before extensive experience with the natural correlations between numbers of objects, spatial extents, and temporal durations.

Our findings raise several questions. First, do human newborns relate numbers and durations to lengths by drawing on a generalized magnitude system that represents these dimensions with a common underlying code (26, 27), or by drawing on separate but linked representations for each dimension? In the mature brain, neural substrates supporting representations of space, time, and number overlap partially, with both common and distinct resources across dimensions, as suggested by clinical studies of patients with neurological damage (28, 29), by functional brain imaging studies of human adults (30), and by electrophysiological studies of trained, adult monkeys (31, 32). Studies of infants do not yet reveal whether infants also have both common and distinct representations of these dimensions. Second, are spatial, temporal, and numerical values calibrated in an absolute way, or are these pairings malleable, such that mappings across these dimensions can be established on any arbitrary values, provided the mappings are congruent? For adults, there is a host of evidence for relative mappings between number and space (11, 15, 18, 33), time and space (14, 34, 35), and number and time (36); hints for absolute cross-dimensional mappings have been also described (37). For infants, this question has yet to be investigated. Third, whereas adults can form translations between any dimensions of magnitude (38), it is not clear whether infants are similarly flexible. Current findings indicate that infants can map three pairs of extensive dimensions—number and space (16, 17), time and space (17, 22), and number and time (17)—and one pair of intensive dimensions—brightness and loudness (39)—but they may fail to relate dimensions belonging to different categories—loudness and length (22) or number and brightness (40). Finally, it is not clear whether the abilities shown by newborn infants are unique to our species or shared by other animals. Although experienced animals of many species link spatial, temporal, and numerical information (41–43), research to date does not reveal whether inexperienced, controlled-reared animals do so. The present paradigm provides the methods to address these questions.

Our findings reveal that the cognitive capacities to link the dimensions of number, space, and time are not founded on extensive postnatal experience in an environment in which these dimensions are correlated. Although a fetus may receive experience of numerical magnitudes and temporal durations in the auditory modality before birth, our experiments tested newborns on their ability to map number and duration on a visual spatial extent, a dimension they encounter only after birth. The predisposition to relate longer lengths to larger numbers and to longer durations might be the result of an associative learning mechanism that, rapidly and within the first hours of life, is tuned to congruent changes across the dimensions of space, time, and number. Alternatively, the sensitivity to the common structure of these dimensions might be present from birth, as part of the evolutionary endowment of human cognition.

Methods

Participants. A total of 96 healthy full-term newborn infants (45 girls) participated in this study (mean age, 51.9 h; range, 7.8–94.5 h; range of weight, 2,720–4,420 g). For each experiment, a new group of 32 infants was tested. All infants had an Apgar score of at least 9 after 5 min. Infants were recruited directly inside the maternity ward, with the authorization of the director of the maternity department at Hôpital Bichat. The research was approved by the Institutional Review Board Ile de France II (Université Paris-Descartes), and informed consent was obtained from a parent of each infant. Those whose mothers had major complications during pregnancy and those with medical problems were excluded from the study. Another 32 infants were brought to the testing room but failed to complete the experiment because they fell asleep or cried. Finally, an additional 30 newborns were excluded after completion of the experiment because of experimenter error or equipment failure (4), drowsiness/fussiness (16), at-ceiling looking times (8), or because offline recoding showed unclear looking behavior (2) (see *SI Methods* for details).

Displays. In experiments 1 and 2 (Movies S1–S8), the sounds used for auditory stimuli were sequences of syllables, repeated either 6 or 18 times (see refs. 8 and 10 for studies using the same syllable sequences). In experiment 3 (Movies S9–S12), we presented sounds made of two syllables separated by a tone of variable duration (short, 1,000 ms; long, 3,800 ms; total duration, 1,400 ms for the short sequence; 4,200 ms for the long sequence). The silence between two sequences varied randomly between 2 and 3 s. Eight different syllables pronounced by male and female speakers were used. Each participant was familiarized to one numerosity/temporal duration and was tested with the other one. In experiment 1, the duration of individual syllables was similar in both numerical/temporal sequences so that the total duration of the sequences was shorter for the 6-syllable sequence (1.4 s) and three times longer for the 18-syllable sequence (4.2 s). In experiment 2, the duration of individual syllables across the 6- and the 18-syllable sequence was manipulated such that the total duration of the sequences was the same (4.2 s). The visual stimuli were colored, horizontally displayed rectangles of a variable length (short, 8 cm; long, 24 cm) presented centered on the screen against a black background, to create vivid color contrasts. The colored rectangles were animated with a stroboscopic movement, not synchronous with the syllable repetitions (see refs. 8 and 10 for similar stimuli design). The order of the first numerosity/temporal duration presented was counterbalanced across participants.

Procedure. The paradigm had two phases: a familiarization phase (60 s) immediately followed by a test phase. During familiarization, each infant received a single auditory numerosity and/or duration paired with a single visual length. Afterward, during test, the auditory numerosity and/or duration changed (from small to large or from large to small) and was paired with the familiar and the novel visual length in two successive trials. Compared with familiarization, test trials thus contained either one change (auditory change only) or two changes (auditory and visual changes). Crucially, two familiarization conditions were created such that, in the two-change trials, the auditory numerosity/duration and visual length either changed in the same direction (either both increasing or both decreasing), or in opposite directions (one increasing, the other decreasing) (Figs. 1 and 2). The order of the test trials was counterbalanced across participants. Each test trial continued until the baby had been looking for one minute or had stopped to look for two seconds consecutively.

Infants were placed in an infant seat, 60 cm from a 22-inch monitor, and an experimenter stood behind the infant to monitor for potential signs of discomfort. A second experimenter situated behind the monitor coded the newborn's looking times online (looking to a monitor displaying infants' faces) 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 another experimenter, from the video record played at slow speed. Because newborns' looks are not always easy to code (if the eyes are not wide open), and online coding was necessarily permissive (for example, if an infant sneezed, the experimenter did not stop the trial), a third offline coding was performed when the two first coders' judgments differed by more than 5 s (22% of all trials). All coders were blind to the visual, but not the auditory stimuli. The analyses reported are based on the average of the two closest measurements for each trial (the correlation between the two measurements was R^2 = 0.98, with a slope of 1 for experiment 1; R^2 = 0.98, with a slope of 0.98 for experiment 2; R^2 = 0.98, with a slope of 0.97 for experiment 3). If the infant presented signs of distress or drowsiness, the experimenter who coded the looking times online terminated the study before it was completed. The second/third coders, who were blind to the experimental conditions, decided when an infant who had completed the study was too drowsy/fussy to be included in the data analyses. We performed Grubbs' tests (α=0.05, two-sided) on looking times during test trials for experiment 1 (M = 30.93; SD = 20.54; Z = 3.22), experiment 2 (M = 31.92; SD = 18.15; Z = 3.22), and experiment 3 (M = 33.58; SD = 19.56; Z = 3.22), and no outliers were detected in any of the three experiments (see Tables S1–S3 for individual looking times in experiments 1–3, respectively).

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