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A Left Visual Advantage for Quantity Processing in Neonates

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Abstract

Forty-eight newborn infants were tested in one of three multimodal stimulus conditions, in which auditory quantities were presented alongside visual object arrays in two test trials. These tests varied with respect to which side (either left or right) numerically matched the auditory number. The infants looked longer to the test trials in which the left side of the visual display exhibited a quantity that matched the presented auditory quantity. This study provides the first evidence for an untrained, innate bias for humans to preferentially process quantity information presented in the left field of vision.

Keywords

Space; Number; Quantity; Magnitude; Neonates; Lateralization

Introduction

The relation between mental concepts of space and number is evolutionarily and developmentally privileged; it has been crystallized into the popular conception of a ‘mental number line’ in Westernized adults wherein small numbers are associated with the left side of visual space, and large numbers the right^{1,2}. Work on populations with little-to-no interaction with the world has documented a similar tendency to spontaneously map quantity to a spatial continuum. Experimentally naïve young chicks³ and monkeys⁴ possess a bias to start their search for food on the left side of a set of locations and progress towards the right, seemingly “counting” rightward³. Newborn chicks also preferentially orient to small numbers on the left side, and large numbers on the right⁵. Work by de Hevia and colleagues^{6,7,8,9} has demonstrated this left-to-right mental number line in infants as well. Infants learn to order a set of arrays if they are presented from smallest on the left to largest on the right¹⁰, but not vice versa, and are quicker to attend to a left-side probe after central presentation of a small number vs. central presentation of a large number (but not a small object vs. large object 6). In a recent study, newborn infants preferentially viewed more-

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Competing Interests

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numerous arrays placed on the right side of space, and less-numerous on the left, suggesting that we selectively map few to left and more to right even during the first few days of life¹¹ (see also ref. 12). For these young populations, this lateralized relationship is present only when discrete quantity is introduced as a variable to be represented, suggesting that space and number have a uniquely close relationship^{9, 13–18}.

According to an evolutionary theory of the mental number line¹⁹, a bias to initially fixate on the left side of space is paired with a bias to prefer sequences that increase in magnitude^{20,21}, and thus it is in part a *spatial bias* that yields lateralized processing of number seen in infancy. Several theorists have posited the existence of an innate visual processing advantage for the left side of space^{22,23}, due to the left visual hemifield being preferentially processed by the right hemisphere of the brain (which is especially dominant for global spatial-attentional processes²⁴ and quantity processing²⁵). This lateralized processing is especially pronounced when mentally organizing quantities, as seen by a leftward bias when bisecting number lines in near space^{26,27}. The existence of a general bias towards the left hemifield of vision has been documented in the first year of life for faces^{28–30} and patterns³¹. It is heightened when the task requires holistic processing of stimuli³², and exacerbated when initially orienting to a stimulus³³. In some studies, it is pervasive^{31,34}. For example, infants orient first, and gaze longer, to the left side of everyday objects, upright and inverted faces, and non-human animal faces³⁴. Thus, there is evidence that we have evolved a *left visual advantage*, present in infancy. To date, however, there is no evidence that this phenomenon is innate, forming the basis for interactions with the world from birth and providing a key component for the early mental number line. Here, we probe for the existence of this left visual advantage in the very first days of life.

Method

We adapted previous methods that probed numerical processing in human newborns across sensory modalities; in particular, newborns fixate longer to visual numerical arrays that match in number an auditory sequence of tones³⁵. We reasoned that if newborns present a left visual advantage, then they would fixate longer to a visual stimulus when its left side contained the same numerical magnitude as an auditory numerical sequence, as opposed to when the same stimulus was inversely oriented (i.e., presenting the critical numerical information on its right side). The auditory stimulus is the “cue” for the infant to use to intermodally match a visual magnitude, and is present in both a familiarization phase (auditory quantity only) and during a testing phase (auditory + visual quantity). Further, drawing from the literature on left visual advantage in older infants and children, we decided to primarily focus on methods that utilize a chimera stimulus^{36–38}. In these types of displays, a bilateral visual stimulus is uneven around a vertical axis, and flipped along this axis for each test trial to ensure maximal similarity on all dimensions *except* laterality. Early work using chimera-type displays emphasized the use of a serial presentation, tachistoscopically³⁹, because this increases the distinctiveness of the two visual hemifields. However, free-viewing of chimeras is also implemented in the literature, and also yields left visual advantage effects^{40,41}.

Because it was unclear how these newborn infants would be interpreting the scenes, with respect to placing their attention, three stimuli sets were created to test for the presence of this left visual advantage. In Experiment 1 (Bilateral With Fixation), the infants had a centralized fixation point (a 4 cm red star) present during the auditory familiarization period and testing trials, and the display off- and on-set every 10 seconds. The chimeric nature of the stimuli was implemented to encourage global processing, which in other populations increases right hemispheric engagement, and the subsequent left visual advantage^{33,42}. The display offset and onset of Experiment 1 aimed to encourage initial orienting behavior, which is especially prone to a leftward bias³³. In Experiment 2 (Bilateral No Fixation), the same design was used, but the infants saw this fixation point only during familiarization, and the displays were not off- and onset periodically. We removed the fixation point for Experiments 2 and 3 out of concern it may influence their tendency to perceive simply the salient red star instead of the whole scene (critical for the LVA phenomenon). The on- and off-setting of the visual stimulus was removed as well, due to concerns of potential disengagement during the viewing of the stimuli. In Experiment 3 (Unilateral No Fixation), the infants saw the fixation point during familiarization, but not test, and the arrays were no longer in the form of a bilateral chimera. Here, the less-numerous and more-numerous sets were presented serially across the two test trials, on either the left or right side of the screen. In this way, we simplify the task for the infants, using stimuli that lessened the lateralized competition of the presented set. For all three experiments, it is hypothesized that infants will look longer to test trials in which the left-side visual quantity matches the auditory quantity. (See Fig. 1 for the displays and designs for each experiment and trial type.)

Participants

A total of 48 healthy, full-term newborn infants successfully completed the study (16 for each experiment; 27 female; mean age = 42.2 hours/31.2 minutes; range = 9 hours 53 minutes to 82 hours 4 minutes). An a-priori power analysis in G*Power⁴⁴ was conducted to arise at this number of participants, with 2 measurements (left-side looking, right-side looking), 12 groups (boys and girls, in 6- or 18-familiarization conditions, in 3 experiments), power of 1-Beta = .80, effect size $f = .4$, and alpha error probability .05. Forty-nine other newborns were recruited and tested but excluded for sleepiness (9), lack of interest in the stimuli (3), crying (9), looking times exceeding the maximum trial length on both test trials (10), experimenter error (6), fussiness (5), postural bias (5) and parental interference (2). All infants had an Apgar score of 10 after 10 minutes. Infants were recruited directly inside the maternity ward, with the authorization of the director of the maternity department at L'Hôpital Bichat-Claude Bernard, Paris, France. All infants were tested in the presence of the mother or father; informed consent was obtained under IRB #00001072 from the institution of the last author.

Stimuli

Numerosities were presented auditorily in the form of sequences of syllables, repeated either 6 or 18 times (see de Hevia et al., 2014, 2017; Izard et al., 2009 for studies using the same syllable sequences). Eight different syllables pronounced by male and female speakers were used. The duration of individual syllables was similar in both auditory sequences such 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). Therefore, the auditory sequences contained information from both numerosity and temporal information. The silence between two sequences varied randomly between 2 and 3 s.

We conducted three different experiments that were identical for the familiarization phase but differed in the test phase (see Fig. 1). For Experiments 1 and 2, visual stimuli (chimeras) consisted of numerical arrays that contained overall 24 items, and individual elements were spatially arranged in such a way that the left and right sides of the array contained 6 and 18 elements. For Experiment 3, visual stimuli (unilateral arrays) consisted of only one part of the chimeras used in Experiments 1 and 2, therefore containing only either 6 or 18 elements. We used four different stimulus configurations in order to avoid perceptual preferences for specific visual patterns. The visual stimuli were formed by colored circles measuring each 2.2 cm and moving as an array stroboscopically every 1 second.

Design and Procedure

The paradigm had a familiarization phase (60 s) immediately followed by a test phase (two trials). During familiarization, each newborn heard auditory sequences of syllables, either 6 or 18 syllables, paired with a centered, rotating visual star. Test trials *contained the same auditory stimulus as familiarization*, now paired with a visual numerical array, presenting the numerosity that matched the auditory stimulus on the left on one trial and on the right on the other trial (bilateral chimeras for Experiments 1 and 2, and unilateral arrays for Experiment 3). The order of the test trials was counterbalanced across participants and familiarization types. Each test trial continued until the baby looked away for two consecutive seconds, or until a maximum trial length of 60 s.

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. Another experimenter, placed behind the stimuli screen, coded online looking times from the image of a camera directed to the infant's face. Another experimenter coded looking times offline, from the video recording 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 experimenter coded looking times offline 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. Coding was not done for side of screen, but rather whether or not the infant was looking at the screen, or not (so, an 'on-off' coding scheme). The analyses reported are based on the average of the two closest measurements for each trial (the correlation between the two measurements was $R^2 = 0.99$ for all conditions). If the infant presented signs of distress or drowsiness, the experimenter who coded the looking times online terminated the study before it was completed. Offline 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.

Results

The data were analyzed in a repeated-measures ANOVA over participants' looking times with a within-subject factor of Target Side (Left, Right) and between-subjects factors of Experiment (Bilateral With Fixation, Bilateral No Fixation, Unilateral No Fixation), Familiarization Condition (6 sounds, 18 sounds), and Sex (Female, Male). There was a significant main effect of target side ($F(1,42) = 4.77, p = .039$, partial $\eta^2 = .12$). Overall, these newborns looked longer to the screen when the image presented had a visual magnitude on the left side of space (either of the chimera display, or of the screen in general) that matched the auditory magnitude that played in the background during familiarization and test (Left Side = 43.1 sec, SEM = 2.6; Right Side = 35.0, SEM = 2.9). Of the 48 infants, 30 looked longer when the target appeared on the left side relative to the right side ($p = .055$, one-side binomial sign-test). There was no interaction of this Target Side factor with Experiment, Familiarization Condition, or Sex. There is an interaction between the between-subjects factors of Experiment and Familiarization Condition ($F(2,36) = 4.49, p = .02$, partial $\eta^2 = .20$). Pairwise comparisons, Bonferroni-corrected for multiple comparisons, reveal that infants familiarized to 6 sounds exhibited different looking times across experiments; specifically, infants in the Unilateral No Fixation experiment who heard 6 sounds looked longer to the screen than infants in the Bilateral No Fixation experiment. In the Bilateral With Fixation experiment, infants looked for 43.9 sec [SEM = 4.0] to the Left-Side target and 37.8 [SEM = 4.5] to the Right-Side target. In the Bilateral No Fixation experiment, infants looked for 39.5 [SEM = 4.4] to the Left-Side target and 27.9 [SEM = 4.9] to the Right-Side target. In the Unilateral No Fixation experiment, infants looked for 46.0 [SEM = 5.2] to the Left-Side target and 39.4 [SEM = 5.8] to the Right-Side target. Looking at each experiment individually, paired t-tests over the looking time to test trials with left-side targets vs. trials with right-side targets reveals no main effect in the Bilateral With Fixation experiment ($t(15) = .84, p = .21$), a marginally significant main effect in Bilateral No Fixation experiment ($t(15) = 1.75, p = .05$) and a significant main effect in Unilateral No Fixation experiment ($t(15) = 2.03, p = .03$). (See Fig 2. for the data, for each Experiment.)

Discussion

In the present study, we adopted the use of chimeric stimuli to ask whether neonates would guide their behavior by preferentially orienting towards the left side of a numerical array. Since newborns preferentially fixate a visual numerical array that matches a concomitant auditory numerical sequence³⁵, we asked whether they would look longer to a stimulus whose left side contains the target number relative to the chimera version containing it on its right side. Across three experimental conditions, we found a general preference for fixating the visual stimulus whose left side numerically matched the auditory numerical sequence. This finding constitutes preliminary evidence for human newborns spontaneously privileging the left side of visual stimulation, and extends previous findings of this phenomenon in older infants for faces and patterns to numerical/quantity information.

Although we observed a general left-sided advantage across the three experiments, it is important to note that the present findings were not as strong as other phenomena recently

described in human newborns using similar methods^{11,35}. There are two main classes of thought as to why this may be the case. First, the newborn left visual advantage may genuinely be a weak effect, not just statistically but in the mind of the infants. This bias may be present, but only seen on a larger population (N= 48, and not N=16 within each experiment), because it is small or fragile, and additional power is needed to detect it reliably. Second, the attenuated nature of the effect may be due to the fact that in our design there were likely different conflicting processes at play in the infants' minds. First, the visual chimera that conform to the canonical left-to-right oriented mental number line (e.g., contain fewer objects on the left side and more on the right side) might have been treated differently than the paired chimera that was inversely oriented. In fact, a preference for small visual numbers to appear on the left side and large visual numbers on the right side has been recently described in newborns¹². Our methods were not designed or appropriately powered to control or test for this variable, however.

Another caveat to consider in our study is that it is conceivable that newborns formed a numerical representation of the entire array in Experiments 1 and 2 whose numerical value (24) was indistinguishable from the auditory number in the 18-syllable sequences, but easily distinguishable from the 6-syllable sequences. If infants were perceiving the test array as '24' (instead of a chimera of 18 and 6), then an increase from 6 auditory tones during familiarization to 24 objects at test would have prompted fixation to the *right* side of the screen¹¹, dampening the finding of a left visual advantage. This is supported by an examination of how the infants behaved in each familiarization condition; the left visual advantage at test for the infants familiarized to 6 was a mean of 6.4 seconds, whereas the difference between left and right fixation for infants familiarized to 18 was 10.6 seconds. This interaction was not significant within the model, but the overall pattern does suggest that other factors within this design were 'working against' our predicted effect. The chimeric nature of the stimuli was implemented to encourage global processing (which increases right hemispheric engagement, and the subsequent left visual advantage^{33,42}), but may have ultimately led to some infants perceiving only the entire array as one single magnitude. Going forward, we are planning future experiments in which the stimuli are more segregated into left and right percepts by increasing the saliency of the two different parts, either by spatially separating them or using different colors for each side.

It is worth noting that our visual stimuli confounded continuous extent (the area taken up by the set) and number (the number of discrete units in the set). In the subfield of numerical cognition, this distinction becomes important, because many theorists have argued that infants either have^{45–48} or do not have^{49,50} truly numerical representations that are abstract, and not simply based on perceptual cues such as size, density, or contour length. In the current study, we were solely focused on providing as many cues to quantity as we could to the child, to prompt a strong left visual advantage, insofar as it existed. Future work would aim at disentangling whether both sources of magnitude information contributed to the effect, or only one source of information gave rise to it. Our hypothesis is that this is a non-specific phenomenon that applies to *any* visual information presented to the newborn infant. However, previous work has found that only the presence of numerical information gave rise to a lateralized spatial mapping of quantity¹¹, which calls for a deeper investigation of this

phenomenon to examine whether the left visual advantage is found here only because we included discrete magnitudes as part of the test stimuli.

In sum, we provide here the first evidence for a left visual field processing advantage in the first days of human life. Although we must interpret this new finding cautiously, given the overall strength of the effect, we believe it is in accord with a theory that helps to explain the presence of a mental number line in similar untrained populations. This finding suggests that the nature of visual processing in infancy has behavioral continuity with a prominent visual bias found later in development. It provides an example of how the neural systems devoted to different types of information in the environment are on-line from the first hours of life, and how these systems impact the nature of more-mature systems later in development.

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Figure 1.

Infants were familiarized with a target number of tones, without any visual arrays present. The visual arrays then appeared in the test trials, and moved stroboscopically every 1 second. The tones played throughout the testing trials. Three versions were created, as it is unclear whether at test infants need frequent onsets of the array while fixating (Exp 1), need a fixation point for focus on the center of an array (Exp 1 and 2), or will naturally fixate on the center of the whole screen (Exp 3). Test stimuli consistent with a left visual advantage are bordered in green for this figure.

Figure 2.

Infants' looking times when targets (the visual quantities that matched the auditory quantities) were presented on the left or right side of the screen, as a function of experiment. Error bars represent ± 1 SEM. The † indicates a significant difference at p -value $< .10$, and the * indicates significance at p -value $< .05$.