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RESEARCH ARTICLE

Are infants' preferences in the number change detection paradigm driven by sequence patterns?

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Abstract

Inter-individual differences in infants' numerosity processing have been assessed using a change detection paradigm, where participants were presented with two concurrent streams of images, one alternating between two numerosities and the other showing one constant numerosity. While most infants look longer at the changing stream in this paradigm, the reasons underlying these preferences have remained unclear. We suggest that, besides being attracted by numerosity changes, infants perhaps also respond to the alternating pattern of the changing stream. We conducted two experiments ($N = 32$) with 6-month-old infants to assess this hypothesis. In the first experiment, infants responded to changes in numerosity even when the changing stream showed numerosities in an unpredictable random order. In the second experiment, infants did not display any preference when an alternating stream was pitted against a random stream. These findings do not provide evidence that the alternating pattern of the changing stream contributes to drive infants' preferences. Instead, around the age of 6 months, infants' responses in the numerosity change detection paradigm appear to be mainly driven by changes in numerosity, with different levels of preference reflecting inter-individual difference in the acuity of numerosity perception.

1 | INTRODUCTION

All humans possess a "number sense": a capacity to perceive and manipulate the approximate number of objects in collections without counting (Dehaene, 2011). This capacity is present in children before formal education and can be traced back to infancy (e.g., Feigenson et al., 2004; Izard et al., 2009; Libertus & Brannon, 2010; Lipton & Spelke, 2003; Xu & Spelke, 2000; Xu et al., 2005). Acuity for perceiving numerosity improves over the course of development. When tested with visual arrays, children display the ability to discriminate numerosities contrasting in a ratio of 1:4 at 4 months, 1:2 at 6 months, 2:3 at 9 months, 3:4 at 3 years, and 5:6 at 6 years, while adults can easily detect numerosities in a 10:11 ratio (Halberda & Feigenson, 2008; Xu & Spelke, 2000; Xu et al., 2005; Wang & Feigenson, 2021; for a review; see Piazza, 2011). Around these general milestones, however, individuals show different levels of numerical acuity (e.g., Halberda et al., 2012). These differences have been shown to correlate with children's level of achievement in school mathematics, a finding with important educational implications (Halberda et al., 2008; Inglis et al., 2011; Lourenco et al., 2012; Starr et al., 2013; Starr et al., 2017; for meta-analyses: see Fazio et al., 2014; Schneider et al., 2017).

In 2010, Libertus and Brannon introduced a paradigm suitable to measure inter-individual differences in numerosity processing in infancy, the "number change detection" paradigm (Libertus & Brannon, 2010). In this paradigm, infants are presented with two streams of images showing arrays of dots on their left and on their right. One of the streams (the changing stream) shows arrays that alternate between two numerosities (e.g., 8-16-8-16 etc.) while the other stream (the constant stream) stays numerically constant (e.g., 8-8-8-8 etc.). Consistent with previous results, the authors found that infants looked longer at the numerically changing stream for a 1:2 numerosity ratio at the age of 6 months and for a 2:3 ratio at the age of 9 months.

Importantly, looking preference was correlated across individuals between these two ages: infants who looked longer at the 1:2 changing stream at 6 months also looked longer at the 2:3 ratio at 9 months. This first result was extended in a second longitudinal study (Starr et al., 2013), where infants' preference for the changing stream at 6 months was found to predict performance at 3.5 years in both a numerosity perception task and, more importantly, in standardized tests of symbolic mathematical abilities. This result is taken as one of the strongest demonstrations that numerosity perception is a predictor of later mathematics achievement (for convergent evidence, see Elliott et al., 2019).

However, the mechanisms driving infants' preference for the changing stream remain unclear—thus raising questions about the interpretation of the inter-individual differences observed. One possibility is that infants simply respond to changes between images: when they see a change between two consecutive images (e.g., a change in numerosity), their attention is captured and they continue to look. Consequently, inter-individual differences in the change detection paradigm would reflect infants' different levels of acuity for detecting numerosity changes. This interpretation, which is currently held by most researchers, leaves however two puzzling findings unexplained. First, many authors have observed that some infants prefer to look at the constant stream over the changing stream, and these preferences can be quite strong (e.g., Decarli et al., 2022; Libertus & Brannon, 2010). If infants' preferences are driven by the detection of numerosity changes, however, this should not happen: individuals who are able to detect the changes in numerosity should prefer the changing stream, and individuals who cannot discriminate between the two numerosities presented should look equally at the two streams. Second, infants displaying strong preferences for the constant stream tend to later show lower scores in mathematics (Starr et al., 2013). Again, there is currently no explanation for this finding. A strong preference for either stream indicates that infants were able to discriminate between the two numerosities presented. If children's inter-individual differences in mathematics are predicted by the acuity of their numerosity representations as infants, then performance in mathematics should be related to the strength of infants' preference for one or the other stream, not to the direction of this preference.

To make sense of these findings, here, we propose an alternative hypothesis: that infants' looking behavior does not mainly reflect their detection of numerical changes but rather their detection of the alternating pattern of the changing stream (ABABAB). More specifically, we hypothesize that infants generally prefer the changing stream not only because they are attracted by changes in numerosity but also because this stream has an interesting alternating pattern. As will be developed below, appealing to the sequence pattern can potentially explain why some infants display a preference for the constant stream, and why infants preferring a constant stream may later show lower performance in mathematics.

Why should infants generally prefer to look at alternating over constant sequences? Several studies have shown that infants' looking times to sequences of stimuli are modulated by the predictability of the items presented (Kidd et al., 2012, 2014; Poli et al., 2020). For example, in two experiments, Kidd et al. (2012) measured 7- and 8-month-olds' attention to sequences of images that varied in predictability: some images appeared very frequently and were thus highly predictable, while others were either moderately or highly infrequent. Infants were most attracted to the images that were just somewhat predictable, but not too much: they tended to look away from the stream when the image presented was either too predictable or totally unpredictable. This preference for an intermediate level of predictability (the "Goldilocks effect") may reflect a powerful learning strategy, where infants actively seek stimuli offering optimal learning opportunities (Gottlieb et al., 2013; Hunter & Ames, 1988; Poli et al., 2020).

While current demonstrations of the Goldilocks effect have focused on the predictability of single items within a sequence, the same effect may occur at the sequence level: very simple (thus fully and easily predictable: e.g., AAAAAAA) or random (fully unpredictable: e.g., ABBABAA) sequences may raise less interest compared to sequences of medium complexity (e.g., ABABABA), whose items are harder to predict.[1]

To this date, however, only few studies have been conducted to test this idea. The first study tested 5-month-olds' responses to sequences of images (simple colored shapes) that were either organized in bigrams or fully random (Addyman & Mareschal, 2013). The authors found that infants looked longer at random sequences and that they tended to look away from bigram sequences specifically when the same bigram was repeated several times in a row. From these findings, they concluded that 5-month-olds did not respond to the bigram structure of the sequences and simply looked away when the same few images were presented repeatedly. As an alternative interpretation, however, it is possible that infants responded to the structure of the sequences in Addyman and Mareschal's (2013) study, but in line with the Goldilocks effect, they lost interest when the sequence became too simple and predictable.

A second study provides suggestive evidence in that direction (Mendelson, 1986). Two groups of infants aged 4 or 8 months were presented with objects animated with different rhythmic movements:

[1]The notion of "stimulus complexity" has been operationalized in different ways in the infant cognition literature (e.g., Kidd et al., 2012; Hunter & Ames, 1988). To design the present experiment, we relied on "algorithmic complexity", an index borrowed from computer science, which has proven to be a good predictor of sequence processing in children and adults (e.g., Amalric et al., 2017; Kempe et al., 2015; Planton & Dehaene, 2021). Formally, the algorithmic complexity of a sequence is defined as the length of the shortest algorithm that can generate this sequence. For instance, alternating sequences are quite low in complexity because they can be generated by short algorithms (e.g., "repeat [AB]"). Constant sequences have even lower algorithmic complexity, while the algorithmic complexity of a random sequence is higher, because there is no simple algorithm that can generate those sequences. Algorithmic complexity is related to item predictability: a sequence of low complexity can be generated using a simple rule, and once one has discovered this rule, it becomes easy to predict the items of the sequence. The lower the algorithmic complexity, the simpler the rule, and the easier it is to predict the sequence items.

a constant/low complexity rhythm (2-2-2-2; i.e., II II II II), an alternating/medium complexity rhythm (3-1-3-1; i.e., III I III I), or an irregular/high complexity rhythm (3-2-1-2; i.e., III II I II). Interestingly, infants' preferences were modulated both by the complexity of the sequence and by age: 4-month-old infants looked longer at the pattern of medium complexity, while 8-month-old infants looked more at the high complexity pattern. These findings fit well with the hypothesis that infants display the equivalent of a "Goldilocks effect" in their responses to whole sequences: infants seemingly prefer to look at sequences that are neither too simple nor too complex for their stage of development. In addition, these findings also suggest that infants' preferred level of complexity for sequences increases with age, in line with classical findings on infants' preferences for visual stimuli (e.g., Brennan et al., 1966; Hunter & Ames, 1988), and with the predictions of computational theories (Gottlieb et al., 2013).

In the particular case of the numerosity change detection paradigm, we suggest that infants generally look longer at the alternating stream because sequences alternating in numerosity correspond to their preferred level of complexity.[2] As alluded to before, this hypothesis can account for the preference to the constant stream observed in some infants: perhaps these individuals prefer to look at the constant stream because the alternating stream is too complex for them. As such, these infants would be lagging behind their peers developmentally, not in the acuity of their number sense but rather in their ability to process sequence patterns. Under this interpretation, children's lower achievement in mathematics could sometimes stem from an initial difficulty with patterns, and the number change detection paradigm predicts mathematical abilities not only because it measures the acuity of infants' numerosity representations but also because it measures their ability to process patterns. Interestingly, in line with this interpretation, several recent studies found a correlation between preschoolers' mathematical abilities and their patterning abilities (e.g., Rittle-Johnson et al., 2019; Wijns et al., 2021).

Understanding the reasons for infants' preferences in the number change detection paradigm is thus crucial to correctly interpret longitudinal results relating infants' responses to children's mathematical abilities. To test the hypothesis that pattern processing contributes to explain infants' preferences, in the present study, we complemented the alternating and constant streams from Libertus and Brannon's (2010) original paradigm with a new kind of stream, where two numerosities were presented in a random, unpredictable order. We tested two predictions: First, if infants looking time solely reflects their detection of numerosity changes, as is often hypothesized, they should prefer a random stream over a constant stream, even though the random stream does not display any regularity (experiment 1). Second, if infants are sensitive to the pattern in sequences of numerosities, and they are specifically attracted to medium complexity alternating sequences, they should prefer an alternating to a random stream (experiment 2).

2 | MATERIALS AND METHODS

2.1 | Participants

Participants were recruited by mail or phone from the greater Paris area. They were aged between 5:15 and 6:15 months:days, were born at term (37 weeks or later), and did not have any health issues

[2]While Addyman and Mareschal (2013) found that 5-month-olds display little interest in sequences of alternating shapes, in the case of numerosity, the stimuli presented (dot arrays) are more complex. If the Goldilocks effect reflects infants' active seeking of stimuli that lay at the verge of their understanding, both item complexity and sequence complexity should contribute to determining infants' preferences. For more complex stimuli (numerosities), infants should thus prefer simpler sequences than for simple stimuli (colored shapes).

TABLE 1 Description of the samples of participants for the preliminary experiment, experiment 1, and experiment 2

	Infants included			Infants excluded			
	Number (Females)	Age	Protocol failure	Parent interference	Total looking time	Left/right bias	Stream preference
Preliminary experiment	8 (5F)	184 days (169–192)	1	3	0	0	Not implemented
Experiment 1	16 (11F)	184 days (171–195)	2	2	3	0	0
Experiment 2	16 (11F)	184 days (169–197)	3	4	0	1	1

as per parental report. Infants were excluded from the analyses in case the paradigm did not unfold as intended (technical failure or experimental error), if parents talked to their child during the experiment, or if parents opened their eyes during stimulus presentation.

In addition, we implemented three exclusion criteria based on infants' looking behavior (modeled after Dillon et al., 2020). The first criterion aimed at excluding infants who were inattentive or drowsy during the task—thus waiving the need for a subjective assessments of "fussiness" or "sleepiness" by the experimenter. To operationalize this, we computed the log of each infant's total looking time (across all experiments) and excluded infants if this index was below the mean of all infants by more than two standard deviations (*SD*). The second criterion excluded infants who had a strong bias to constantly look at the left or right side of the screen. To do so, we computed the absolute log of the ratio of looking times to the right and left sides of the screen and excluded participants if this value deviated from zero by more than two *SD*s. Lastly, since we used *t*-tests comparing preferences to chance as our main analysis tool, and *t* tests rely on an assumption of normality, we excluded outliers within each experiment. Infants were excluded if their preference for one of the streams (as measured by the log of the ratio of their looking times) differed from the mean preference in this experiment by more than two *SD*s (a similar within-experiment outlier exclusion criterion was also implemented in Libertus & Brannon, 2010). Exclusions are summarized in Table 1.

The present study was conducted according to the guidelines laid down in the Declaration of Helsinki, with written informed consent obtained from a parent or guardian for each child before data collection. All procedures involving human subjects in this study were approved by the Ethical Committee of Université Paris Cité (Comité d'Ethique pour la Recherche de l'Université Paris Cité).

2.2 | Stimuli

Infants were presented with continuous streams of dot arrays on the left and right sides of a large projection screen. Dots were black on a white background. Projected images measured 68 × 51 cms, and were separated by a 43 cm gap. Each array was projected for 500 ms, followed by a 300 ms blank (see Figure 1).

Three types of streams of dot arrays were created: (1) constant numerosity streams, where all arrays had the same numerosity (either 5 or 20); (2) alternating streams, where arrays alternated systematically between 5 and 20 dots; and (3) random streams, where arrays of 5 and 20 dots were presented in a mixed, random order, with an equal number of 5 and 20 s. Each stream was made of a sequence of 24 images, which was repeated twice, for a total duration of about 40 s. Dot arrays varied

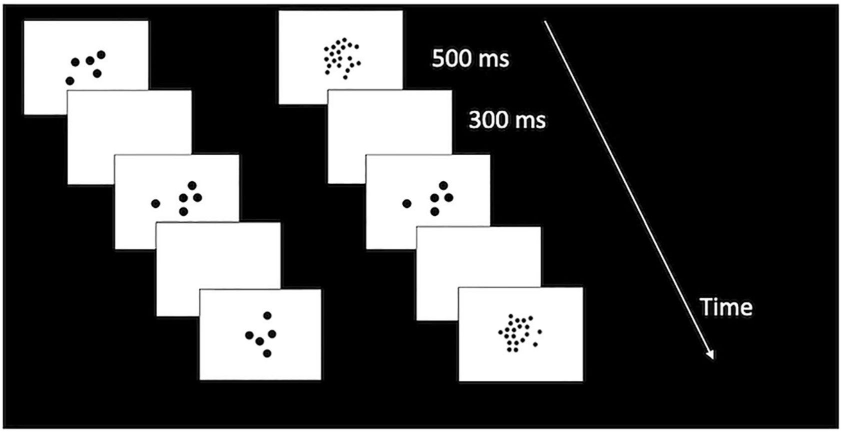

FIGURE 1 Illustration of the number change detection paradigm. Images of dot arrays were shown for 500 ms, followed by 300 ms of blank screen. In this example, a constant stream is shown on the left and an alternating stream on the right. Arrays presented here were equated in extensive parameters

in the nonnumerical parameters of dot size, total area, density, and convex hull. We created two different conditions where stimuli of 5 and 20 dots were roughly equated either on extensive parameters (total area and convex hull) or on intensive parameters (dot size and density). In the extensive parameters condition, dots measured 2.7–4.6 cm (5 dots) or 1.3–2.3 cm (20 dots) in diameter, and arrays covered a circular area of 20–45 cm in diameter. In the intensive parameters condition, dots measured 2.3–4.6 cm in diameter, and arrays covered a circular area of 15–25 cm (5 dots) or 25–50 cm (20 dots) in diameter.

2.3 | Procedure

Each trial started with an attractor image looming at the center of the screen, followed by two streams of images (amongst constant, random, or alternating) projected on the left and right of the screen. Infants received four trials in total. The position of the two types of numerical sequences presented alternated systematically between the left and right sides across trials. Different non-numerical parameter conditions (intensive parameters equated or extensive parameters equated) were used in first and second pairs of trials. The three variables of position order (which type of sequence was first projected on the left), array parameters order (whether the two first trials showed arrays equated on intensive or extensive parameters), and when relevant, numerosity value in the constant sequence (five dots or 20 dots) were counterbalanced across infants. They were assigned automatically by the program such that the experimenter was blind to the position of the sequences. An attractor was shown at the beginning of the experiment and between each trial.

Different infants were tested in different experiments (Preliminary experiment: alternating *vs*. constant, experiment 1: random *vs*. constant, and experiment 2: alternating *vs*. random).

2.4 | Data recording and analyses

To ensure fast decisions on infants' exclusion, live coded looking times were used to compute exclusion criteria. After all infants had been tested, infants' looking behavior was recoded offline by a different trained coder (also blind to the position of the streams) while the video of the infants was played at half speed. Reliability between the two codings was high (Pearson correlation between the two codings, based on looking times to the right and left sides in each trial, $p < 0.001$, $r = 0.94$). The offline coding of looking times, which was presumably more precise, was used to analyze infants' preferences.

To analyze the data in each experiment, we computed the log of the ratio of each infant's accumulated looking times to the two sequences shown (summed across all four trialds). Then, we tested infants' preference against chance (0) by means of a *t*-test. We also report exploratory ANOVAs testing whether the order of the nonnumerical control conditions, the sides of the streams on the first trial, and when relevant, the number of dots in the constant stream had any effect on infants' preference.

The data and the script of the analyses can be found at https://osf.io/awk9r/.

3 | RESULTS

3.1 | Preliminary experiment: Alternating versus constant

In the present study, we used a single large projection screen rather than two separated small screens to present stimuli. To ensure that these testing conditions would give rise to a preference, we first tested a group of eight infants (see Table 1) with constant *vs*. alternating sequences, as in the original number change detection paradigm. Following Libertus and Brannon (2010), the same image was used on both sides when the two streams showed the same numerosity.

The preliminary experiment confirmed that our setup was appropriate to elicit a robust preference for alternating over constant numerosity streams. All infants (8/8) looked longer at the alternating stream than at the constant stream (average log of looking time ratio 0.58, range 0.09–1.22, see Figure 2), a proportion comparable to previous reports (14/16 infants looked longer at the alternating sequence in Libertus & Brannon, 2010).

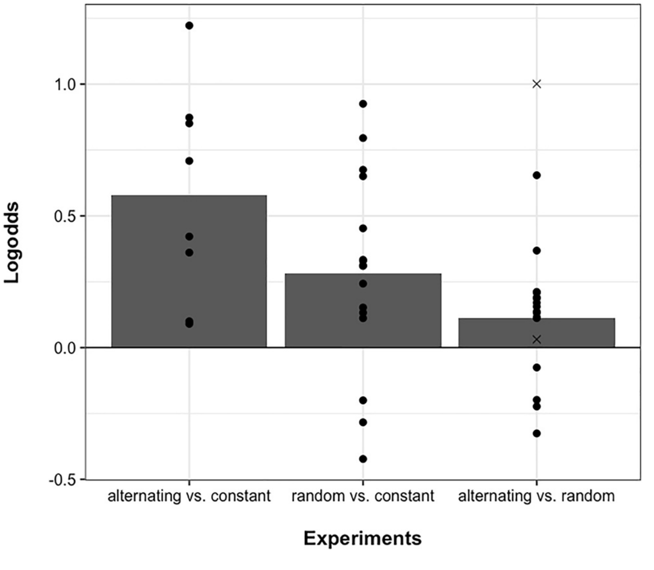

FIGURE 2 Results of the preliminary experiment (alternating vs. constant), experiment 1 (random vs. constant), and experiment 2 (alternating vs. random). Plotted are the log of the ratio of the looking times to the first type of sequence versus the second type of sequence. Bars: average preference across infants. Dots: individual infants' preferences. Cross: individual data for infants who were not included in the main analysis

3.2 | Experiment 1: Random versus constant

Infants looked longer at the random changing stream than at the constant stream, $t(15) = 3.0$, $p = 0.009$, and $d = 0.75$; 13/16 infants looked more at the random stream (average log of looking time ratio 0.28, range −0.42–0.92). Thus, infants' gaze is attracted to changes of numerosity, even when the sequence is not regular.

To test whether the parameters of the task may have influenced infants' preferences, we ran an exploratory 2 × 2 × 2 ANOVA on the log of the looking time ratio with three between-participants variables for the order of the nonnumerical control conditions, the side of the alternating stream on the first trial, and the numerosity of the constant stream (5 or 20 dots). There was no significant effect or interaction associated with these variables, all *F*s between 0.00 and 3.43 and all *p*-values >0.05.

Infants' significant preference for random streams over constant streams indicates that changes of numerosity are sufficient to attract longer looks, even in the absence of a pattern. Still, infants may be sensitive to patterns, in addition to being attracted by numerosity changes—suggestively, the preference appeared stronger in the preliminary experiment (log ratio preference = 0.58), where the changing stream was also regular. We conducted experiment 2 to address this question.

3.3 | Experiment 2: Alternating versus random

The analysis provided no evidence that infants looked differently at the random and alternating streams, $t(15) = 1.9$, $p = 0.073$, and $d = 0.48$; 12/16 infants looked more at the alternating stream (average log of looking time ratio 0.11, range −0.33–0.65). A 2 × 2 ANOVA on the log of the looking time ratio with 2 between-participant variables for order of the nonnumerical control conditions and side of the alternating stream on the first trial indicated that these variables had no effect on infants' preference, all *F*s between 0.03 and 0.9 and all *p*-values >0.05.

The absence of a significant preference between random and alternating streams may indicate that infants did not detect the difference between these two types of streams, or it may result from insufficient statistical power. To try and decide between these two alternatives, we ran an exploratory Bayes Factor analysis including the data from the present group of 16 infants, plus the data of the one infant who had been excluded for outlier preference (as this should not affect the results of a Bayesian analysis) and one infant who was tested after the group was completed. This analysis revealed weak evidence in favor of a preference for the alternating stream, BF = 1.6 (deemed "anecdotal" by Jeffreys's standards, Jeffreys, 1961). In short, our data cannot decide whether infants preferred to look at the regular alternating sequence or displayed no preference.

4 | GENERAL DISCUSSION

Longitudinal studies have shown that infants' preference in the numerical change detection paradigm are stable over time (Libertus & Brannon, 2010) and that the preference of individual infants predicts their school math performance as preschoolers (Starr et al., 2013). However, a characterization of the features driving infants' preferences in this paradigm is lacking. While the mainstream interpretation holds that infants simply respond to changes in numerosity, it is also possible that they rather, or concurrently, respond to the structure of the streams, looking longer at a mildly complex (alternating pattern) than at a simple (constant) stream. Resolving this question is crucial to correctly interpret the findings of longitudinal associations, especially as related to children's later performance in mathematics.

To that avail, we assessed 6-month-old infants' responses in two novel versions of the paradigm, where we presented constant or alternating streams against a stream showing two numerosities in a random, unpredictable order. In experiment 1, we found that infants preferred looking at a random sequence over a sequence constantly showing the same number of dots. Infants thus respond to numerosity changes even in the absence of a predictable sequence structure. In experiment 2, we assessed infants' preference between a random stream and an alternating stream. No significant preference was found between these two streams.

Our findings are compatible with two interpretations. On the one hand, it is possible that infants' preferences in the change detection paradigm are mainly (if not solely) driven by the presence of changes in numerosity. Indeed, if such was the case, infants should prefer looking at sequences changing in numerosity over constant sequences even when the changing sequences are not regular (as found in experiment 1), and they should display no preference between sequences displaying changes in numerosity, whether these sequences are regular or not (compatible with the findings of experiment 2). If this first interpretation is correct, then inter-individual differences measured in the numerosity change detection paradigm reflect differences in the acuity of infants' numerosity perception, and not in their ability to process patterns.

On the other hand, it remains possible that infants responded to sequence complexity in our task but that the complex random streams we presented were actually quite appealing for 6-month-olds, yielding little to no preference when these complex streams were pitted against simpler alternating sequences. More specifically, perhaps 6-month-olds’ preferred level of complexity is larger than the mild complexity of an alternating sequence, or in other words, 6-month-olds would rather look at sequences that are more complex than alternating sequences.

One aspect of our data tends to disprove this second interpretation, however. With age, infants should become able to parse more complex sequences, and thus prefer higher levels of complexity (Brennan et al., 1966; Gottlieb et al., 2013; Mendelson, 1986). If infants' preferences were solely driven by complexity in our experiment, we should thus observe that older infants tend to display stronger preferences for random sequences, compared to younger infants. This prediction was not borne in our data, however. Instead, we observed a reverse trend, with older infants displaying somewhat stronger preferences for alternating over random streams (linear regression, $F(1,15) = 4.2$, $p = 0.058$, see Figure 3). This observation suggests that infants' responses to sequences of numerosity overgo a developmental change around the age of 6 months. Before this age, in line with the mainstream interpretation of the number change detection paradigm, infants' preferences seem to be driven by the mere detection of numerosity changes between images. After 6 months, in contrast, we suggest that the pattern starts playing a role in infants' preferences. Consequently, it is possible that inter-individual differences measured after 6 months reflect differences in infants' ability to process patterns, rather than (or together with) differences in their perception of numerosity.

Why did young infants fail to respond to alternating patterns in our task? There could be two different reasons for this. On the one hand, perhaps sequence patterns have no effect on young infants' looking preferences in general (as argued, e.g., by Addyman & Mareschal, 2013). On the other hand, it is also possible that some infants failed to detect the alternating patterns in our task because their perception of numerosity was too coarse. We tried to avoid this issue by presenting two markedly different numerosities (5 *vs*. 20, a 1:4 ratio, when 6-month-olds typically discriminate numerosities in a 1:2 ratio). Still, it may be that some infants detected only a subset of the changes presented, and thus could not perceive the sequence as a perfectly regular, alternating sequence.

In summary, our study raises the possibility that inter-individual differences in the numerical change detection paradigm do not purely reflect differences in numerosity perception but also reflect infants' ability to process patterns. Correctly interpreting inter-individual differences in this task is

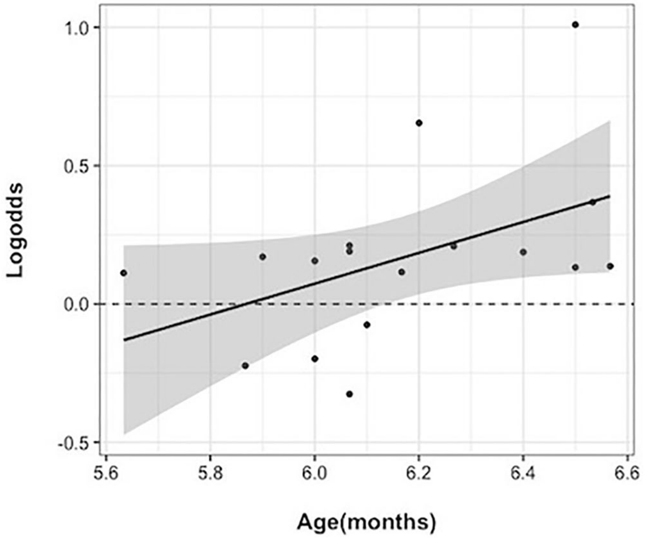

FIGURE 3 Infants' preference for the alternating over the random stream in experiment 2, as a function of age; gray shading represents a 95% confidence interval. The chance level of zero is outside the confidence interval only for ages 6.2 months and above

particularly important, given the findings of longitudinal associations between infants' responses and children's mathematical achievement. We hope that our work will stimulate further research to try and understand the determinants of infants' preferences in the numerosity change detection paradigm, building a solid ground to understand the sources of children's inter-individual differences in mathematics achievement.

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CONFLICT OF INTEREST

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