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The Influence of Memory on Visual Perception in Infants, Children, and Adults

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Abstract

Perception is not an independent, in-the-moment event. Instead, perceiving involves integrating prior expectations with current observations. How does this ability develop from infancy through adulthood? We examined how prior visual experience shapes visual perception in infants, children, and adults. Using an identical task across age groups, we exposed participants to pairs of colorful stimuli and implicitly measured their ability to discriminate relative saturation levels. Results showed that adult participants were biased by previously experienced exemplars, and exhibited weakened in-the-moment discrimination between different levels of saturation. In contrast, infants and children showed less influence of memory in their perception, and they actually outperformed adults in discriminating between current levels of saturation. Our findings suggest that as humans develop, their perception relies more on prior experience and less on current observation.

Keywords: Perceptual development; Bayesian inference; Implicit memory development; Visual perception; Contraction bias

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1. Introduction

To make sense of perceptual input, observers do not merely rely on their current observations. They also integrate prior knowledge into perception—a process that has been called central tendency, tendency toward the mean, and contraction bias (Hollingworth, 1910; Woodrow, 1933). This integration process allows perceivers to overcome the inherent unreliability of their current observations by combining additional sources of information. Differences in reliance on prior experience relate to perceptual differences between neurotypical and atypical populations (Jaffe-Dax, Lieder, Biron, & Ahissar, 2016; Lieder et al., 2019), underscoring the importance of integration processes.

When perceivers efficiently incorporate prior knowledge, they can more easily overcome perceptual noise in the environment (Raviv, Ahissar, & Loewenstein, 2012), but integration requires retaining detailed information in memory and weighing it appropriately. In adults, recent events tend to be weighed heavily, and the influence of prior events decays exponentially across time (Fischer & Whitney, 2014; Lu, Williamson, & Kaufman, 1992; Raviv et al., 2012). For adults with weaker implicit memory, decay usually occurs more rapidly, leading to less reliance on accumulated experience (Jaffe-Dax, Frenkel, & Ahissar, 2017). Children, of course, have less experience than adults and more limited memory (Gathercole, Pickering, Ambridge, & Wearing, 2004; Ofen et al., 2007; Schlichting, Guarino, Roome, & Preston, 2022). However, it is not known whether children, like adults, use prior experience to inform their perception, or whether there are age-related changes in how they do so. We examined the developmental trajectory by which prior knowledge is integrated with new sensory input.

It is broadly believed that memory span and the ability to integrate information across time develop slowly (e.g., Kwon, Reiss, & Menon, 2002; Luciana & Nelson, 1998; Zald & Iacono, 1998). However, it is notoriously difficult to measure perceptual and memory-related capacities in a way that enables comparison of infants, children, and adults, and even more rare to use one experimental task spanning these age groups. Here, we evaluated the influence of memory on infants', children's, and adults' sensitivity to differences in the saturation of brightly colored stimuli. To do so, we designed an infant-friendly, gaze-contingent eye-tracking procedure that exploits the basic perceptual tendency of humans, without training and regardless of age, to be drawn to look at more saturated (vs. less saturated) stimuli (Maule, Skelton, & Franklin, 2022; Werner & Wooten, 1979). This perceptual judgment task allowed us to test whether and how participants' abilities to discriminate the relative saturation levels of sequentially presented stimuli would be influenced by their accumulated experience with the task. Crucially, our task enabled direct comparison across ages because it is (1) intuitive, with no need for explicit instruction, and (2) does not require extensive training, allowing for the inclusion of infants even if fewer trials are obtained.

Although task demands differ, participants from infancy to adulthood are known to track regularities in their visual environment (Fiser & Aslin, 2002a, 2002b; Jost, Conway, Purdy, Walk, & Hendricks, 2015; Kirkham, Slemmer, & Johnson, 2002; Saffran & Kirkham, 2018; Turk-Browne, Scholl, Chun, & Johnson, 2008). In addition, there is robust evidence that adults can extract summary representations of a group of objects that allow them to estimate averages across multiple features, including size, brightness, and color (Albrecht & Scholl,

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2010; Ariely, 2001; Bauer, 2009; Brady & Alvarez, 2011; De Gardelle & Summerfield, 2011). Adults compute these means rapidly and with high accuracy (Chong & Treisman, 2003; Piazza, Sweeny, Wessel, Silver, & Whitney, 2013), and recent studies suggest that infants and children also learn visual summary statistics (Balas, 2017; Skelton, Franklin, & Bosten, 2023; Zosh, Halberda, & Feigenson, 2011).

These summary representations affect adults' judgments of individual stimuli; for instance, they tend to estimate the size of objects as more similar to the mean of a display (Brady & Alvarez, 2011), the frequency rate of vibrations as closer to the mean rate of the experimental set (Preuschhof, Schubert, Villringer, & Heekeren, 2010), the pitch of tones as closer to the mean pitch (Raviv et al., 2012), and the weight of objects as closer to the mean weight (Woodrow & Stott, 1936). This phenomenon, where events are perceived as closer to the central tendency of previous events of the same type, is termed "contraction bias" (Hollingworth, 1910; Woodrow, 1933). Likewise, the presence of similar items in working memory can bias adults' judgments in a visual perception task (Teng & Kravitz, 2019). However, it is not yet known whether infants and children, who may have more difficulty remembering previous items, show similar biases in their perception.

In the current study, we sought to investigate the developmental emergence of contraction bias and to determine whether prior experience exerts a similar influence on infants', children's, and adults' visual perception, using the same task across age groups. To explore the role of prior experience in visual perception, we used a gaze-contingent eye-tracking procedure that tested participants' ability to evaluate relative levels of saturation. On each trial, participants saw two sequentially presented items (colorful pinwheels) that differed in saturation and were presented in different locations. Pinwheels then disappeared, and gray boxes appeared marking their previous locations. We then recorded participants' first shift toward one of the locations as a measure of their judgment of which pinwheel was more saturated (see Fig. 1). While participants did not receive any explicit instructions about the goal of the task, we considered a first shift to the location of the more saturated pinwheel to be a "correct" response, and we defined their accuracy as the probability of choosing the more saturated item in a pair, averaged across trials.

Using this task, we tested whether there were age-related differences in the extent to which participants displayed contraction bias. In our task, this bias would lead each stimulus to be perceived as more similar in saturation to the mean saturation of all previously viewed stimuli. We expected infants and children to show weaker retention of information about previously experienced visual stimuli, and we, therefore, predicted younger participants would show less influence of memory on their in-the-moment perception. A second and related prediction, again resulting from differences in memory capacities, was that younger participants would actually outperform adults in making in-the-moment judgments.

2. Methods

2.1. Participants

Three different age groups participated and were included in the final sample of 72 participants ($n = 24$ in each group): 1-year-old infants (14 female, $M = 11.8$ months, range:

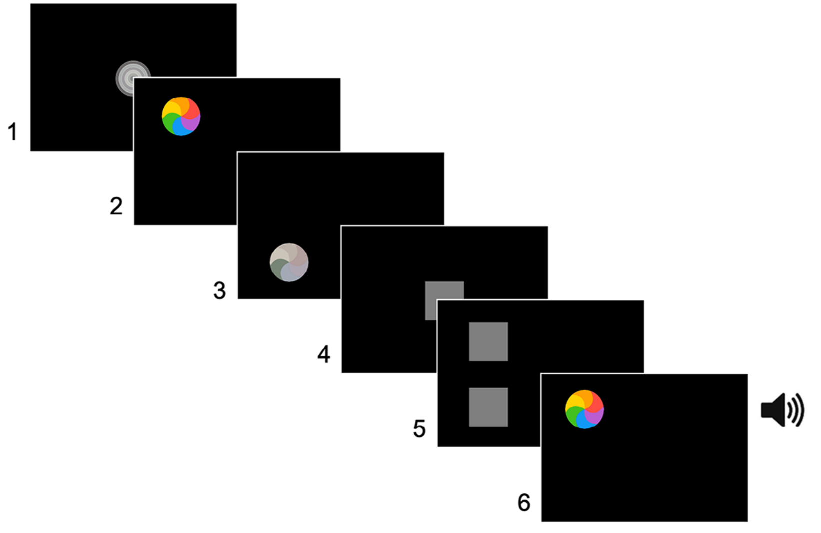

Fig. 1. Schematic illustration of trial structure.

Note. (1) Participants' gaze was drawn to the center of the screen with a gray-scale attractor. (2) First, a pinwheel appeared in one of eight possible locations until the participant fixated on it. (3) A second pinwheel appeared at a different location until the participant fixated on it. (4) Participants' gaze was drawn back to the center. (5) Two masks appeared in the prior locations of the pinwheels until the participant fixated on the location of the more saturated pinwheel, at which point the more saturated pinwheel reappeared, along with a rewarding sound. The location where the participant first fixated was recorded as the participants' choice for that trial.

10.2–13.9 months), 5-year-old children (15 female, $M = 66.3$ months, range: 60.2–71.9 months), and young adults (14 female, $M = 20.6$ years, range: 18.9–25.7 years). A previous study that compared perceptual bias in a related two-interval choice task with three groups of participants (Jaffe-Dax & Eigsti, 2020) yielded an effect size of $\eta_p^2 = 0.19$, which is equivalent to *Cohen's* $d = 0.96$. This study suggests that to achieve a power of 1-$\beta = 0.8$, we needed a sample size of at least $N = 19$ per group. Informed consent was obtained from adult participants or from guardians for the younger age groups. Assent was obtained from the participating children. All participants received $10 in compensation, and infants and children also received a small gift. Prior to recruitment, all procedures were approved by the Princeton University Institutional Review Board. Twenty-four additional participants were tested but excluded for: unsuccessful calibration (4 infants), failure to provide at least 10 usable trials (11 infants, 5 children), overall inattentiveness (2 children), or vision that was not normal or corrected-to-normal (2 adults).

2.2. Experimental design

Each trial began with a neutral gray-scale attention-getter in the center of the screen. Once the participant fixated on it for 300 ms, the first colorful pinwheel was presented in one of eight possible locations on an imaginary circle around the center of the screen, and it remained

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there until the participant fixated on it for 300 ms. We used eight different locations to discourage pattern-seeking behavior. Indeed, when we debriefed our adult participants, none mentioned location on the screen as a meaningful factor. Then, the first pinwheel disappeared and the second pinwheel was presented in one of the remaining possible locations (not including the immediately adjacent locations) until the participant fixated on it for 300 ms. The two pinwheels differed in their levels of saturation. A second central attention-getter was presented until the participant fixated on it for 300 ms. Two gray squares were then presented in the same two locations where the two pinwheels had appeared. We recorded the first square that the participant fixated for 300 ms as their "choice" for that trial. For example, if the participant fixated on the square that appeared in the same position as the first pinwheel, the recorded choice was "first." After the participant looked at the gray box in the location of the more saturated pinwheel, that pinwheel reappeared and a rewarding sound was played. Rewarding sounds were random selections of pleasant stimuli, such as chimes. Fig. 1 depicts a schematic illustration of a trial. The next trial commenced when the participant fixated again on the attention-getter in the center of the screen.

The task began with pairs of pinwheels that had relatively large differences in saturation, and differences lessened over the course of the experiment, thereby increasing the difficulty of the task as time went on. All pinwheels were variations of the same image, and the saturation level—defined as the S value in the HSV (Hue, Saturation, Value) representation of the image—of one of the stimuli was randomly drawn from a uniform distribution between 0.1 and 1. The ratio between the two saturation levels within the trial was initially drawn from a uniform distribution between [2, 4]. Then, as the experiment progressed, the discrimination task became incrementally more difficult; specifically, the range of the distribution decreased every 10 trials to [1.75, 3], then [1.5, 2.5], then [1.25, 2], then [1.2, 1.75], and finally [1.1, 1.5] from trial 61 through the end of the experiment. Note that the decrease in the range of saturation level difference was not dependent on participants' performance. Finally, the order of the presentation of the two pinwheels was randomly chosen.

On 80% of trials, the two pinwheels had different saturation levels. Half of these trials showed the more saturated pinwheel first; the remaining half of the trials presented the more saturated pinwheel second. If the participant first looked to the more saturated pinwheel, that pinwheel reappeared in the same location along with a rewarding sound (Fig. 1). If it was the less saturated pinwheel, the squares remained on the screen until the participant fixated the target location, at which time they saw the pinwheel reappear and heard the rewarding sound. Trials ended after 4 s if the participant did not make any choice.

On 20% of trials, the two pinwheels had the same saturation level ("equal-saturation trials"), and participants saw the pinwheel and heard the sound in whichever location they fixated first, given that each location was equally correct. The purpose of equal saturation trials was to examine participants' biases toward previously presented stimuli when there was no objective difference between the pinwheels. However, these trials did not yield meaningful results in a planned separate analysis, likely due to the small number of trials that were included in it (infants: 4.7 ± 2.5, children: 8.3 ± 4.6, adults: 17.7 ± 2.5; mean number of usable equal trials $\pm$ STD).

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2.3. Procedure

All participants sat approximately 60 cm from the monitor and eye tracker (Eyelink 1000 Plus, SR Research, Ontario, Canada). The monitor measured 34 cm by 27 cm and eye gaze was recorded using the 25-mm infant lens. The display monitor was facing the participant. The host monitor and computer were in front of the experimenter, facing away from the participant. Before beginning the experiment, a 5-point calibration was used. We performed calibration and validation for all participants and did not exclude participants based on validation accuracy.

Infants sat on their caregivers' laps throughout the experiment. Caregivers were instructed to not interfere with the infant and wore a visor during the experiment, which prevented them from seeing the screen and blinded them to the content of the individual trials, to avoid biasing the infants' behavior. Children and adults sat on a chair. The experimenter watched the participant from the Eyelink host computer in order to execute recalibration or to exit the experiment when infants or children became too inattentive and fussy. Monitoring the host computer also allowed the experimenter to adjust the display monitor as infants or children moved. In order to equate the conditions across age groups, no instructions were given and no explicit feedback was provided.

Participants were presented with a maximum of 105 total trials with incrementally increasing difficulty levels every 10 trials. Infants contributed fewer trials than children, and, in turn, children completed fewer than adults (infants: 29 $\pm$ 14.7, children: 58.4 $\pm$ 29.9, adults: 101.6 $\pm$ 3.8; mean number of completed trials $\pm$ STD). No equal-saturation trials were presented in the first five trials of the experiment. After the first five trials, one equal-saturation trial appeared in each block of five trials in a random position within the block, with the stipulation that there were never back-to-back equal-saturation trials.

By capitalizing on the automatic tendency to prefer more versus less saturated colors, we were able to measure informative responses throughout the task without requiring a training phase and without explicit instructions. After the experiment, we debriefed adult participants and asked them: 1. "What did you think the study was about?" 2. "How did you decide which square to look at?" 3. "When did you hear a sound play?" 4. "Did you notice anything else?" Based on these four questions, we identified five adult subjects who explicitly linked saturation with the occurrence of the target sound (e.g., one of them replied to the second question: "I would look at the brighter pinwheel."). We controlled for this possible confound in a control analysis by replacing the participants who reported explicit understanding of the task with new participants.

2.4. Statistical analysis

We excluded trials where the participant took longer than a predefined threshold of 1 s to make a choice (infants: 29.3 $\pm$ 11.6, children: 41.8 $\pm$ 10.2, adults: 22 $\pm$ 13; mean % of excluded trials $\pm$ STD), in line with previous work involving similar tasks (Jaffe-Dax, Raviv, Jacoby, Loewenstein, & Ahissar, 2015). We attributed longer responses to either inattentiveness or technical measurement error. Delayed responses to the stimuli render the contraction bias intractable, given that time delays lead to decay in the representations of both stimuli.

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After this exclusion, infants contributed an average of 20.5 trials (± 10.6; STD), children contributed an average of 32.5 trials (± 17.6), and adults contributed an average of 78.4 trials (± 13.5).

We measured performance for each participant by averaging their accuracy (i.e., probability of first looks to the location of the more saturated stimulus) on all trials with response times of < 1 s. We also calculated each participant's average response time for all correct trials (including all response times).

We then analyzed participants' choices using two predictors (Fig. 2): β_1—within-trial physical difference in saturation between the two pinwheels (i.e., perception), and β_2—between-trial bias, which captured the contraction of the saturation level of the first (stored; to-be-compared) pinwheel toward the mean saturation of previously viewed pinwheels (i.e., the impact of memory; Raviv et al., 2012). The first predictor captured the physical distance in saturation level between the two pinwheels in the current trial and was defined as $\Delta S_t = \log(s_t^1) - \log(s_t^2)$, where s_t^1 and s_t^2 are the saturation levels of the first and second pinwheels in trial t, respectively. Log transformations were used because discrimination judgments depend on the ratio between the intensity of the discriminable feature of the stimuli instead of the difference between them. The second predictor captured the contraction of the mental representation of the first pinwheel toward previously viewed pinwheels from earlier trials. The representation of the first pinwheel decays relative to the representation of the second pinwheel (i.e., earlier presented information is less accessible), thus its contraction toward the mean is greater, that is, prior perception exerts a larger influence. This predictor was defined as: $\Delta Mean_t = \langle \log(s) \rangle_t - \log(s_t^1)$, where $\langle \log(s) \rangle_t$ is the average of all saturation levels of pinwheels that were presented up to trial t, where: $\log(s)_t = \frac{1}{2(t-1)} \sum_{i=1}^{t-1} [\log(s_i^1) + \log(s_i^2)]$. This predictor represents perceptual contraction toward the central tendency of the first pinwheel, or summary statistical learning (Hollingworth, 1910; Woodrow, 1933; Fig. 2). It is important to note that the two predictors are independent, such that variation in in-the-moment discrimination (β_1) is not tied to variation in the influence of prior experience (β_2). That is, a participant could score high or low on either predictor.

We regressed each individual's probability to fixate on the first-presented pinwheel using these two predictors to measure the relative contributions of current observation (β_1) and recent visual memory (β_2) on performance. The weight of the first predictor corresponds to how accurately participants were able to distinguish between saturation levels. We included this measure instead of relying on a traditional percent correct because trials had unequal difficulty, and difficulty increased incrementally after each block of 10 trials; simply reporting accuracy would be misleading. Moreover, on the 20% of equal-saturation trials where the two pinwheels had the same saturation, there was no "correct" response, so this measure more meaningfully captures participants' performance. The weight of the second predictor represents the contraction of the mental representation of the first pinwheel toward the mean of all previously presented pinwheels.

2.5. Code and data accessibility

Original code and data are available at: https://osf.io/xvk5e/?view_only=366ec42cec044555a3112b354314756c

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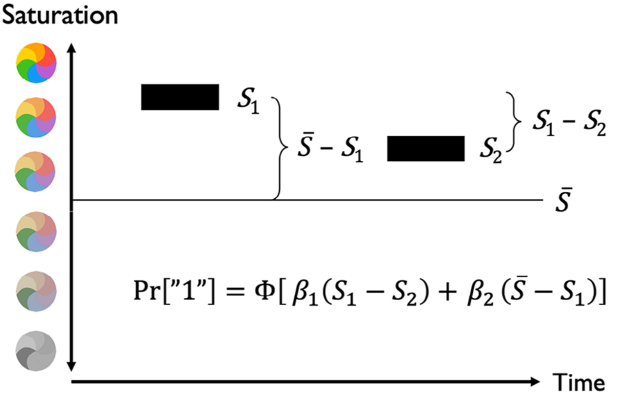

Fig. 2. Definitions of predictors for participants' choices.

Note. This figure illustrates trials with stimuli whose saturation is above the mean of all previous trials. β_1 captures the weight of the current saturation difference between the two stimuli in the current trial (roughly, the slope of the psychometric curve as a function of saturation difference). β_2 captures the weight of integration of previous stimuli in the current observation (impact of prior experience).

3. Results

3.1. Overall performance in the visual perception task

Infants and children performed more accurately on the visual perception task than adults, choosing the position of the more colorful pinwheel more often when the pinwheels differed in saturation [69.7 ± 13.8, 72.6 ± 12, and 57.8 ± 13.5; % correct ± STD for infants, children, and adults, respectively; Fig. 3A; $F(2, 69) = 8.8$, $p < .0005$, $\eta^2 = 0.2$, *Cohen's* $d = 1$]. Specifically, adults had higher accuracy than infants [$t(46) = 3$, $p < .005$] and children [$t(46) = 4$, $p < .0005$], while the latter two groups did not significantly differ in accuracy [$t(46) = 0.8$, *n.s.*; two-sample *t*-test]. That is, although adults tend to outperform infants and children on most tasks, they were actually *less* likely than infants and children to discriminate between saturation levels within pairs of pinwheels (i.e., they were less likely to fixate the placeholder of the more saturated pinwheel within a pair).

Importantly, participants of all age groups performed the task well. In fact, even on the first trial, prior to any information about the audio contingency, participants already tended to choose the more saturated pinwheel (infants: 78.6%; children: 60.0%; adults: 83.3%), suggesting that infants' children's and adults' preference was automatically drawn toward pinwheels of greater saturation.

Children were numerically slower than both infants and adults to choose the position of the more colorful pinwheel (0.89 ± 0.39, 1.24 ± 0.38, and 0.77 ± 0.38; reaction time in seconds ± STD for infants, children, and adults, respectively; Fig. 3A). However, this difference was not statistically significant [$F(2, 69) = 0.9$, *n.s.*]. This pattern of results implies a modest inter-subject speed-accuracy tradeoff effect between younger participants and adults when

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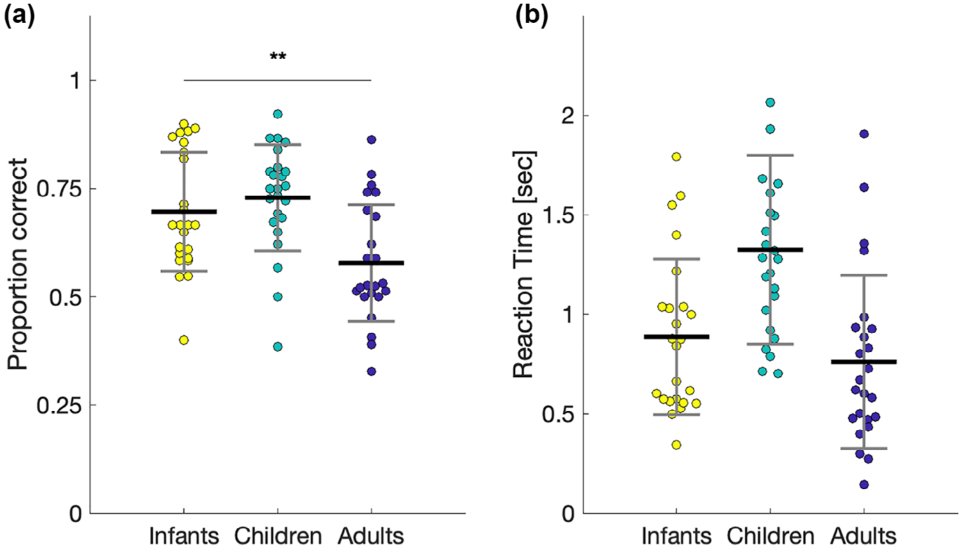

Fig. 3. General performance in the visual perceptual task.

Note. (A) Individuals' proportion of correct responses when reaction time was less than 1 s, by group. (B) Individuals' mean reaction time for correct responses with no reaction time limit, by group. Black lines represent groups' mean. Gray lines represent ± STD. Post-hoc comparisons: $**p < .005$; $***p < .0005$.

considering overall perceptual performance; that is, children performed more accurately but numerically more slowly, possibly reflecting their particular combination of automatic and strategic processes. When considering both accuracy and speed together, infants were the best performers in the task (Fig. 3).

3.2. *Impact of memory on visual perception*

We analyzed all single-trial data (of all difficulty levels) using linear mixed-effects models with subject as a random effect. We regressed participants' responses in each trial (first look toward the "1st" or "2nd" gray placeholder) on two predictors: (1) the difference between the saturation level of the two pinwheels in the current trial; (2) the difference between the mean saturation level of all previous trials. We found the weights of each predictor using a mixed model with subject as a random variable: Resp ∼ deltaCurrent + deltaMean + Group:deltaCurrent + Group:deltaMean + (1 | Subject). All groups showed a significant tendency to look first at the more saturated pinwheel within a trial [$F(1, 3125) = 48.4$, $p < 10^{-11}$; Fig. 4A], demonstrating that across ages, participants were able to perceive differences in saturation and perform the task appropriately. In fact, even on the first trial, prior to any information about the reward contingency, participants already tended to choose the more saturated pinwheel (infants: 78.6%; children: 60.0%; adults: 83.3%), suggesting that infants' children's and adults' preference was automatically drawn toward pinwheels of greater saturation. Despite increasing difficulty, performance level remained quite stable across the

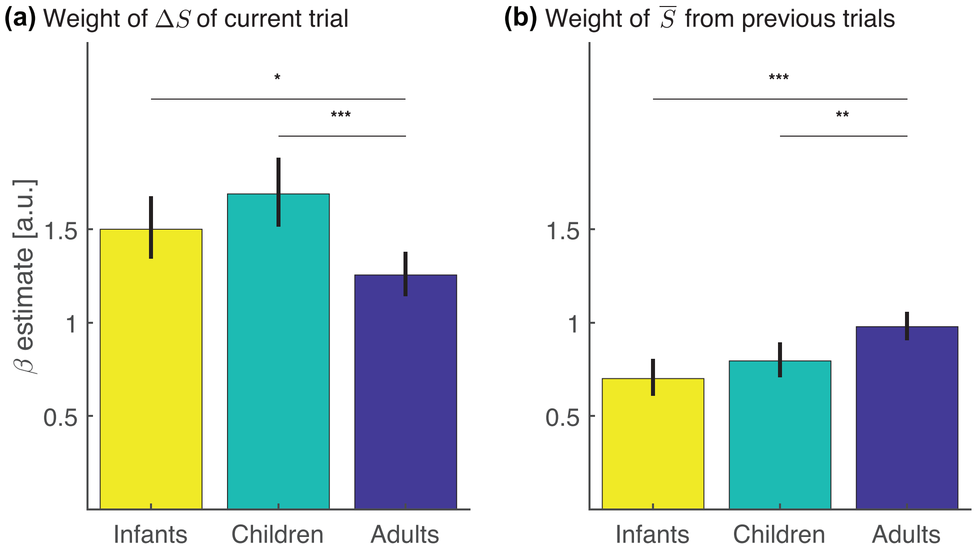

Fig. 4. Weight, by age group, of current trial (saturation difference) and of previous trials (mean saturation level) in predicting participants' choices.

Note. (A) Weight of the saturation difference (ΔS) in the current trial in predicting participants' choice. (B) Weight of mean saturation level ($\bar{S}$) from previous trials (i.e., merging the representation of the first pinwheel's saturation level in the current trial toward the mean of all previous saturation levels in predicting participants' choice). Error bars denote 95% confidence interval. Post-hoc comparisons: $^{*}p < .05$; $^{**}p < .01$; $^{***}p < .0001$. This pattern of results was replicated when the number of trials for each group was equated by matching participants based on their number of completed trials and when adult subjects who reported an explicit understanding of the task were replaced with new participants.

experiment (see Figs. S1 and S2), reflecting consistent sensitivity to saturation differences, as well as perceptual learning as trials increased in difficulty over the course of the experiment (Ahissar & Hochstein, 1997). We also found significant contraction toward the mean of previously presented stimuli for all ages ([$F(1, 3125) = 23.9$, $p < 10^{-5}$; Fig. 4B], but not toward a specific stimulus in the past [Fig. S6]), suggesting that memory influenced performance in all three age groups. But critically, we found that the impact of current saturation differences (i.e., current observation) differed between age groups [$F(2, 3125) = 8.4$, $p < .001$, $\eta_p^2 = 0.05$, *Cohen's d* $= 0.45$]. Specifically, infants and children showed greater influence of the current saturation level on their performance on a given trial, relative to adults [adults vs. infants: $F(1, 2354) = 5.4$, $p < .05$; adults vs. children: $F(1, 2647) = 15.9$, $p < .0001$; children vs. infants: $F(1, 1249) = 2.5$, $p = .11$; Fig. 4A].

Importantly, we also found that the impact of prior perception differed between the three age groups [$F(2, 3125) = 10.2$, $p < .0001$, $\eta_p^2 = 0.18$, *Cohen's d* $= 0.95$]. While all groups showed a significant impact of prior experience on perception, adults showed significantly greater bias toward the mean saturation of all preceding trials, relative to infants and children [adults vs. infants: $F(1, 2354) = 16.2$, $p < .0001$; adults vs. children: $F(1, 2647) = 8.9$,

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$p < .01$; children vs. infants: $F(1, 1249) = 1.6$, $p = .21$; Fig. 4B]. In line with our prediction, we found that adults were more likely to apply information from their aggregate prior experience compared to children and infants. This came with a cost for adults' sensory perception in the moment. However, this is not necessarily a net disadvantage, given that reliance on prior experience is often an efficient way to navigate incoming input (Ahissar, Nahum, Nelken, & Hochstein, 2009).

3.3. Control analyses

We conducted four control analyses to confirm that our findings reflect an influence of memory on visual perception. First, differences in the number of completed trials across participant groups could have resulted in a less accurate representation of the mean saturation level, which might account for the lower weight of incorporating that mean estimate into in-the-moment perception. In addition, because the difficulty of trials increased as the experiment progressed, participants who completed more trials had to judge pairs of stimuli that were closer in their saturation levels, which could have affected their overall performance. To address this possible confound, we performed additional analyses in which we accounted for variability in the number of usable trials across participants and groups. We did so by matching each infant with both a child and an adult based on the number of usable trials, and we omitted trials from the older participants after the target infant's final trial. That is, if the target infant completed 29 trials, we removed any trials beyond that trial number for the paired child and adult. We conducted this matching procedure to ensure that groups matched in the average number of completed trials, variance of the number of completed trials, and physical difficulty level of completed trials. Results obtained using this reduced dataset were consistent with the effects reported in the primary analysis [$F(2, 1458) = 4.6$, $p < .05$, $\eta_p^2 = 0.12$, *Cohen's d* $= 0.75$; see Figs. S3 and S4], suggesting that group differences were not due to differences in the number of trials contributed by each age group.

In our second control analysis, we evaluated whether performance was influenced by the different number of trials completed by each age group, which could have made the representation of the prior more reliable for older participants. We addressed this concern by using only one preceding trial as the prior for the current trial. That is, instead of bias toward the mean, we estimated the bias toward the immediately preceding trial. Results obtained using this alternative definition of prior were consistent with the effects reported in the primary analysis [$F(2, 3084) = 7.1$, $p < .001$, $\eta_p^2 = 0.14$, Cohen's $d = 0.81$], suggesting that group differences were not due to differences in the total number of trials completed by each age group.

A third control analysis examined whether adults may have relied on explicit expectations or understanding of the task in a way that affected their perceptual inferences. Based on the debriefing questionnaire, we excluded five participants who expressed some sort of explicit understanding of the task structure, and we replaced them with five new participants who did not report any understanding of the task. The inclusion of these new participants did not change the reported group differences [$F(2, 3068) = 10.8$, $p < .10^{-5}$, $\eta_p^2 = 0.19$, *Cohen's d* $=$ 0.96; see Fig. S5], suggesting that the observed group differences were not due to explicit

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versus implicit knowledge about the task, in line with recent work showing no effect of explicit feedback on contraction bias in perceptual tasks (Loewenstein, Raviv, & Ahissar, 2021).

Finally, we explored whether variability in participants' response times (particularly the overall slower responses of children compared to both infants and adults) may have contributed to observed group differences in the contraction bias. To address this potential confound, we checked whether the strict 1 s response-time threshold for trial exclusion could have influenced our conclusions. Using a more liberal threshold of < 2 s, we found the same pattern of results [$F(2, 3580) = 2.9$, $p < .05$, $\eta_p^2 = 0.07$, *Cohen's* $d = 0.6$], suggesting that the original trial exclusion criterion of response time < 1 s did not bias the results.

4. Discussion

Using an identical task with 1-year-old infants, 5-year-old children, and young adults, we examined the influence of prior visual experience on visual perception. We found that all groups showed a contraction bias; their perception was skewed toward the mean of all previously experienced exemplars. In addition, we found that bias increased with age, revealing that adults weighted their memory of prior events more heavily in perceptual judgments. Strikingly, infants and children actually outperformed adults in discriminating between different levels of saturation, and their performance was less biased by previously experienced exemplars. Thus, recent visual memory already influences visual perception in infancy, but exerts greater influence with development.

One construal of our results is that younger participants were less able to incorporate memory into their perception, but within this construal, there are several nonexclusive possibilities: infants and children may have had weaker representations of prior events, *or* they may have weighted past experience less, instead focusing on in-the-moment saturation levels. Indeed, infants and children selected the more saturated pinwheel more accurately than adults. This effect may even have been generated by infants' and children's increased motivation to hear the rewarding sound, but prior studies indicate that such rewards are insufficient to facilitate perceptual improvement (Reetzke, Maddox, & Chandrasekaran, 2016; Vernetti, Smith, & Senju, 2017). Regardless, the performance of younger participants suggests that their in-the-moment visual perception was more precise and less susceptible to interference from past experience. Therefore, immature memory and reduced integration of prior knowledge may directly or indirectly enhance the acuity of in-the-moment visual discrimination.

What explains this pattern of performance? One possibility is that changes in memory span shape perception. That is, prior information, built up from trial to trial, may be less available to infants and children. Prior studies offer contradictory evidence as to whether there are significant changes in the structure and mechanisms of early memory (Nelson, 1995; Rovee-Collier, 1997; Rovee-Collier, Hartshorn, & DiRubbo, 1999; Vöhringer et al., 2018), but there is consensus that infants build knowledge across sequentially presented stimuli (Lew-Williams & Saffran, 2012; Maye, Werker, & Gerken, 2002; Thiessen & Saffran, 2007) and that the ability to retain information over longer periods improves with age and experience (Beckner

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et al., 2020; Gathercole et al., 2004; Simmering, 2016). Younger learners might retain weaker representations of previously experienced exemplars, such that early events have reduced influence on perception. Combining our behavioral task with neuroimaging methods that track the accumulation of information from trial to trial (Jaffe-Dax, Kimel, & Ahissar, 2018; Lu et al., 1992) could shed light on this possibility. If infants and children showed shorter neural adaptation compared to adults, this would suggest that their accumulation of information over time is weaker. Such a developmental trajectory of an increasing timescale of adaptation could stem from differences at the cellular level, where older neurons are slower to return to their baseline activity levels due to prolonged afterhyperpolarization (Disterhoft, Thompson, Moyer, & Mogul, 1996; Kumar & Foster, 2004; Landfield & Pitler, 1984; Potier, Rascol, Jazat, Lamour, & Dutar, 1992; Power, Wu, Sametsky, Oh, & Disterhoft, 2002), or at the network level, where the cortical connectivity is enriched and becomes more complex over the course of development (Fair et al., 2009; Grayson & Fair, 2017; Sherman et al., 2014). A second possibility is that infants and children do accumulate adult-like knowledge of perceptual experiences, but underestimate its relevance. That is, they may have access to information in memory, but they do not incorporate this longer timescale into their in-the-moment decision (Decker, Otto, Daw, & Hartley, 2016), perhaps due to reduced capacities of executive function in early development (Zelazo et al., 2003). We note that the task we used to measure perception required participants to hold items in memory for a very short period of time, but it is still difficult to infer at what stage perceptual information is incorporated into memory. Namely, it is unclear whether the representation of the prior information is adequately formed during the perception process, but underutilized at younger ages, or whether the information from prior events is less likely to accumulate into a reliable representation among infants and children. Previous neuroimaging studies with clinical populations have suggested that reduced bias toward the prior in these tasks stems from impaired representation of the prior, rather than impaired retention of the current items in memory, or impaired utilization of prior information (Jaffe-Dax et al., 2017, 2018). Regardless of the mechanism, our results show that younger participants were more likely to treat individual trials as discrete events, rather than contingent on the distribution of previous stimuli. This suggests more efficient adaptation to (or more emphasis on) newly perceived events in infancy and childhood versus adulthood.

Across many domains, it has been suggested that immaturity confers benefits in perception and/or learning (e.g., Bjorklund, 1997; Turkewitz & Kenny, 1982; Werker & Tees, 1984), and weaker memory skills in particular have been suggested to contribute to cases where children and infants learn more successfully than adults (Gualtieri & Finn, 2022). For instance, Newport (1990) argues that children's advantage in learning language is in part attributable to their poor working memory because reduced memory for long sequences of speech enables sensitivity to relations among individual units. This proposal is supported by behavioral studies and computational models demonstrating that limits on memory can sometimes support learning (Cochran, McDonald, & Parault, 1999; Elman, 1993; Frank & Gibson, 2011; Kareev, 1995). Our study illustrates another potential benefit of immature memory: the reduction of perceptual biases that could, in turn, limit future learning (Lew-Williams & Saffran, 2012; Potter, Wang, & Saffran, 2017; Thiessen & Saffran, 2007).

That is, through experience, learning can become more constrained (Zettersten, Potter, & Saffran, 2020), and weaker perceptual biases may allow infants and children to be more receptive to learning from unexpected events. Infants and young children rapidly incorporate the novel experience into perceptual judgments (Maye et al., 2002; Potter & Saffran, 2015), and over development, increases in prior knowledge may impede their ability to perceive less-expected events and to acquire new (and potentially unexpected) information. Thus, a reduced reliance on prior perception may allow infants and young children to absorb new knowledge, even if the information is inconsistent with the child's previous experience.

These results also demonstrate that developmental changes in the interaction between memory and visual perception may lead to less precise perception in the moment. This may be comparable to phenomena such as perceptual narrowing (Lewkowicz & Ghazanfar, 2009; Maurer & Werker, 2014), where cognitive development is marked by changes in how accumulated experience shapes processing. Through experience, infants become less beholden to current sensory input and instead rely on prior experience to guide their sensitivity to incoming input (e.g., Bar-Haim, Ziv, Lamy, & Hodes, 2006; Gottlieb, 1976; Pascalis, de Haan, & Nelson, 2002; Werker & Tees, 1984). Our findings suggest that this developmental shift from an emphasis on current information to an incorporation of information across multiple events transcends perception in a way that is inextricably linked to memory. Relatedly, age-related changes occur during memory retrieval, where children draw more from concrete and specific memories, while adults infer related information from broader representations and schemas (Brod, Lindenberger, & Shing, 2017; Schlichting et al., 2022). The current results add evidence that over development, humans learn to integrate their experiences across increasingly longer durations, with both negative and positive effects: this process introduces bias in perceiving new information, yet may enable more informed expectations.

The current study makes two novel methodological contributions. First, we developed a task that does not require training, explicit instructions, or any verbal skills, and thus can be administered to various age groups—potentially including populations that are often challenging to include in laboratory tasks (e.g., minimally verbal individuals, or individuals with developmental disorders, such as autism spectrum disorder). Second, we found a rare case where infants and children outperform adults in a cognitive task. Other cases where younger participants outperform mature learners are often reported when infants or children show sensitivity to information that was previously not relevant, either in the moment (e.g., Roome, Towse, & Jarrold, 2014; Sloutsky & Fisher, 2004) or based on history of exposure (e.g., Kuhl, Conboy, Padden, Nelson, & Pruitt, 2005; Pascalis et al., 2002; Werker & Tees, 1984). Here, we demonstrate that 12-month-old infants' and 5-year-old children's abilities can exceed those of adults when attending to a perceptual dimension (saturation) that should be similarly accessible to each group. Future studies will continue to examine the relative influences of domain-general and domain-relevant experience in determining how learners weight prior experience in their perception of novel events, the role of feedback (or lack thereof) in the development of this weighting, and the role of explicit task knowledge in shaping perception.

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5. Conclusion

Contemporary developmental science emphasizes the complexity of early environments and attempts to explain how infants contend with noisy input across a variety of domains (e.g., Bergelson et al., 2019; Clerkin, Hart, Rehg, Yu, & Smith, 2017). While adults may rely on past experience to overcome noise when making perceptual judgments (Raviv et al., 2012), infants and children have less experience, and their memory capacities are not as robust. Perhaps because of these limitations, they may depend less on prior experience and more on their current observations. Our experiment provides new evidence about how memory and basic perception interact across much of the lifespan. As humans gain expertise in highly practiced domains (here in visual perception, but possibly in other domains; see Maurer & Werker, 2014 for review), they may make greater use of prior experience and less use of immediate perception in navigating the complexities of their input. Going forward, it will be important to investigate if this process of change can help explain individual differences in learning within and beyond the domain of visual perception.

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Conflict of interest

The authors declared that they had no conflict of interest with respect to their authorship or the publication of this article.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplementary information

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