The influence of memory on visual perception in infants, children, and adults

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Article

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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 measured their ability to discriminate relative saturation levels. Results showed that adult participants were biased by previously-experienced exemplars, but 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: visual perception; implicit memory; contraction bias; human development

To make sense of perceptual input, observers do not merely rely on their current observations. They also integrate prior knowledge (Hollingworth, 1910; Woodrow, 1933). The integration process allows perceivers to overcome the inherent unreliability of their representations of current observations by combining additional sources of information. Differences in reliance on prior experience have been linked to perceptual differences between neurotypical and atypical populations (Jaffe-Dax et al., 2016; Lieder et al., 2019), underscoring the importance of these integration processes.

When a perceiver can efficiently incorporate prior knowledge, they can more easily overcome perceptual noise in the environment (Raviv et al., 2012), but integration requires the ability to retain detailed information in memory and weigh it appropriately. In adults, more recent events tend to be weighed most heavily, and the influence of prior events decays exponentially across time (Fischer & Whitney, 2014; Lu et al.1992; Raviv et al., 2012). For adults with weaker implicit memory, this decay usually occurs more rapidly, leading to less reliance on accumulated experience (Jaffe-Dax et al., 2017). Children, of course, have less experience than adults, and they also have more limited memory abilities (Gathercole et al., 2004). However, it is not yet known whether children, like adults, use prior experience to inform their perception, or whether there are age-related changes in how they do so. In the current study, 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 undergo a protracted developmental trajectory. However, it is notoriously difficult to measure perceptual and memory-related capacities in a way that enables comparison of infants, children, and adults, and it is even more rare to use one experimental task spanning these age groups. In this study, we evaluated the influence of memory on infants', children's, and adults' sensitivity to differences in the saturation of brightly colored stimuli. To enable direct comparison between participants of different ages, we developed a new perceptual judgement task that is (1) intuitive, with no need for explicit instruction, and (2) does not require extensive training, thereby allowing for inclusion of infants even if fewer trials are obtained.

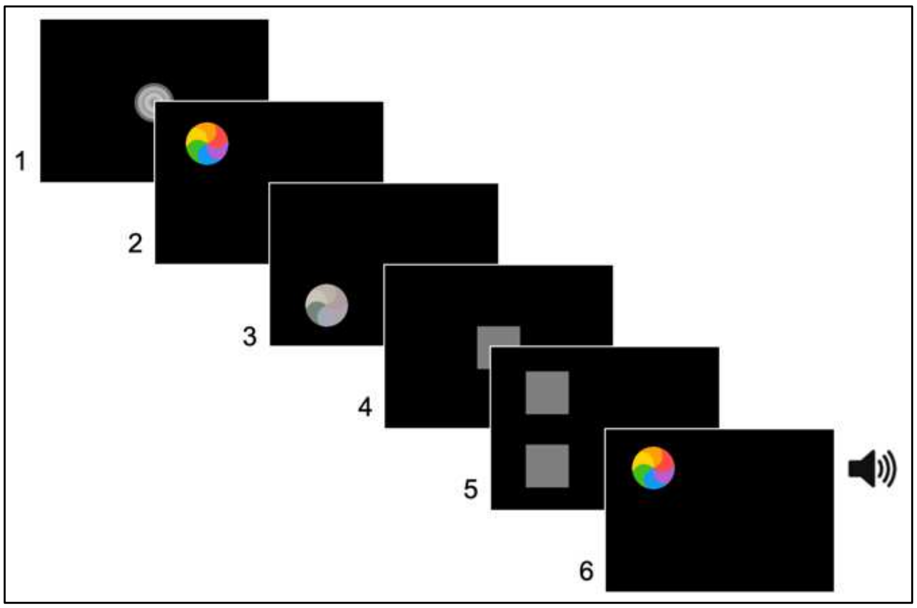
Although task demands differ, participants of all ages, from infancy to adulthood, are known to track the statistics of their visual environment and to successfully detect regularities in their surroundings (Fiser & Aslin, 2002b, 2002a; Jost et al., 2015; Kirkham et al., 2002; Saffran & Kirkham, 2018; Turk-Browne et al., 2008). In addition, there is robust evidence that adults can extract a summary representation of a group of objects that allows them to estimate the average across multiple features, including size, brightness, and color (Albrecht & Scholl, 2010; Ariely, 2001; Bauer, 2009; Brady & Alvarez, 2011; De Gardelle & Summerfield, 2011). Adults compute these means rapidly and with a high degree of accuracy (Chong & Treisman, 2003; Piazza et al., 2013), and recent studies suggest that infants and young children learn visual summary statistics similarly to adults (Balas, 2017; Zosh et al., 2011).

For adults, these summary representations affect their 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 et al., 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 contents of working memory have been shown to influence adults' visual perception such that their judgments in a visual perception task are biased by similarity to recently-viewed items (Teng & Kravitz, 2019). However, it is not yet known whether infants and children, who may have more difficulty tracking and remembering items that they have previously seen, will show similar biases in their perception.

In the current study, we investigated the impact of prior knowledge on visual perception in infants, children, and adults by using the exact same task across all age groups. We tested 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. Our hypothesis was that prior experience would bias perception for all participants and that we would see evidence of contraction bias. In our experiment, this bias would lead each stimulus to be perceived as more similar in saturation to the mean saturation of all previously-viewed stimuli. We also predicted that prior experience would exert the greatest influence on adults' perception, as weaker memory would make younger participants less biased by their previous perceptual experience. Namely, we expected infants and children to less reliably retain information about previously experienced visual stimuli, and we therefore predicted that younger participants would show less influence of memory on their in-the-moment perception. A secondary prediction, resulting from differences in memory capacities, was that younger participants would actually outperform adults in making in-the-moment judgments.

Figure 1

Schematic Illustration of Trial Structure



Note. 1. Participants' gaze was drawn to the center of the screen with a grey 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 re-appeared, along with a pleasant sound. The location where the participant first fixated was recorded as the participants' choice for that trial.

Results

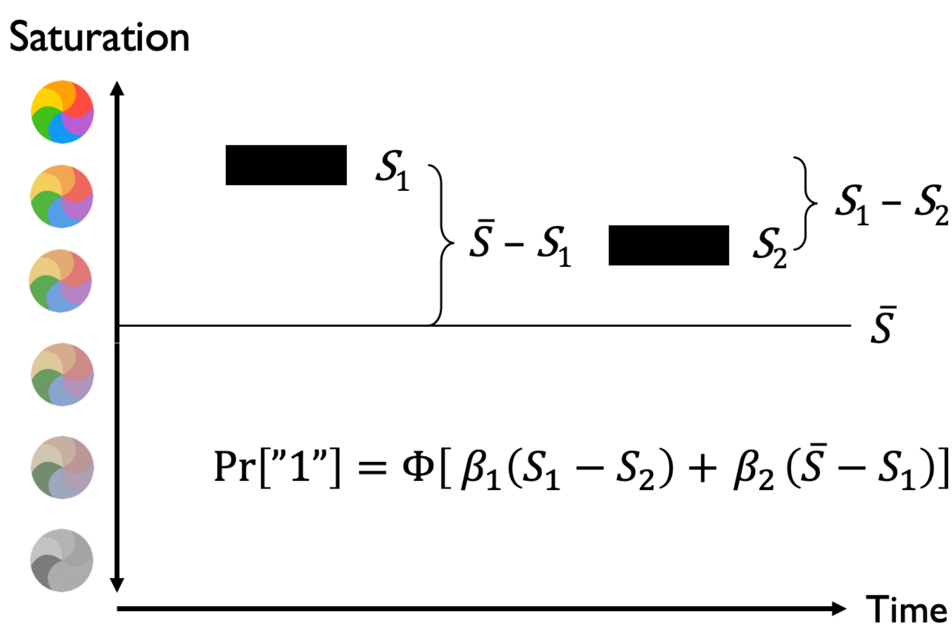
To assess the influence of prior knowledge on visual perception, we designed an infant-friendly, gaze-contingent eye-tracking task that exploits the basic perceptual tendency of humans, without training and regardless of age, to be drawn to look at more saturated (vs. less saturated) stimuli (Werner & Wooten, 1979). Each trial began with a neutral attention-getter in the center of the screen. Then, two colorful rotating pinwheels appeared one after the other in different locations. Each pinwheel appeared until the participant fixated on it, and then disappeared. The two pinwheels differed in their levels of saturation. After participants had viewed both pinwheels, their attention was again drawn to the center of the screen and grey boxes appeared marking the previous locations of the pinwheels. We then recorded participants' first shift toward one of the locations as a measure of their judgment of which pinwheel was more saturated (Fig. 1). After the participant looked at the grey box in the location of the more saturated pinwheel, that pinwheel re-appeared and a pleasant sound was played. 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. We also randomly introduced trials where the two pinwheels had identical saturation ('equal-saturation trials'), which allowed us to examine participants' biases toward previously presented stimuli when there was no objective difference between the pinwheels.

The task was administered to three groups of participants: one-year-old infants, five-year-old children, and young adults (n = 24 in each age group). If a parent or a guardian was present, they were blindfolded and were asked to refrain from directing the participant's gaze. In order to equate the conditions across age groups, no instructions were given and no explicit feedback was provided. By capitalizing on the *a priori*, automatic tendency to prefer more vs. less saturated colors, we were able to measure informative responses throughout the task without requiring a training phase.

We analyzed participants' choices using two predictors: 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 (Weber, 1834). The second predictor captured the contraction of the mental representation of the first pinwheel towards 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, i.e., 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: $\langle \log(s) \rangle_t = \frac{1}{2(t-1)} \sum_{i=1}^{t-1} \left[\log(s_i^1) + \log(s_i^2) \right]$. 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.

Figure 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).

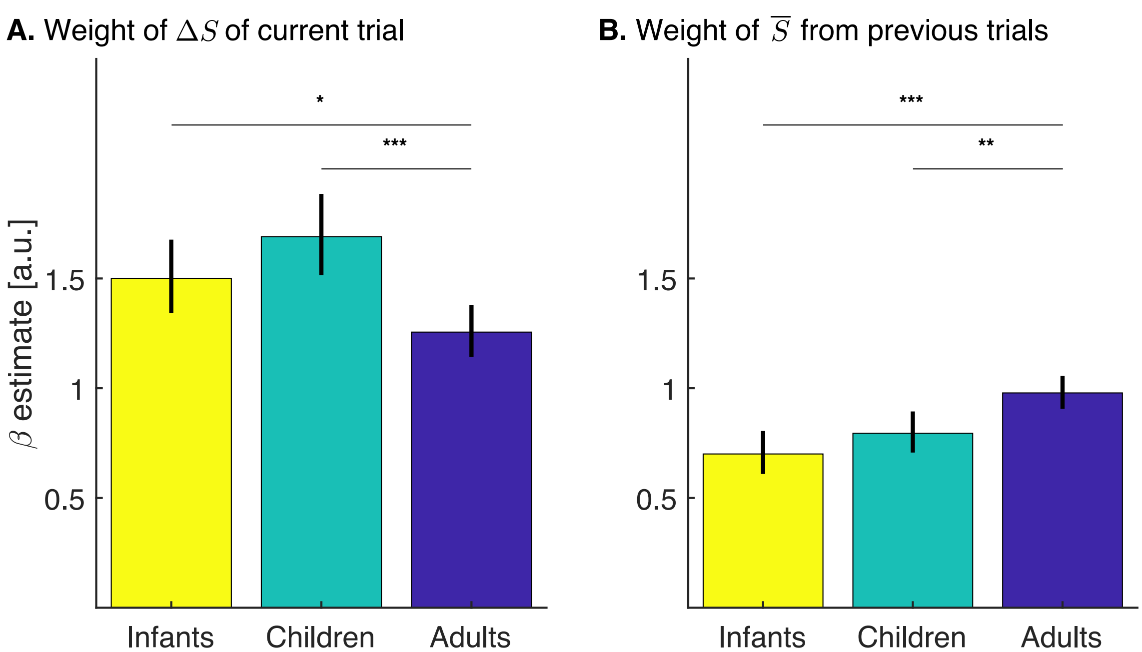
We regressed each individual's probability to fixate on the first-presented pinwheel using these two predictors to measure the relative contributions of current observation (β_1) and memory (β_2) on performance. The weight of the first predictor corresponds to how accurately participants were able to distinguish between saturation levels. We used this measure instead of 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.

We analyzed all single-trial data (of all difficulty levels) using linear mixed-effects models with subject as a random effect. All groups showed a significant tendency to look first at the more saturated pinwheel within a trial [$F(1, 3125) = 48.4$, $p < 10^{-11}$], 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%). We also found a significant contraction towards the mean of previously-presented stimuli for all ages [$F(1, 3125) = 23.9$, $p < 10^{-5}$], 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 [$F(2, 3125) = 8.4$, $p < .001$]. 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. 3A]. 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, we also found that the impact of prior perception differed between the three age groups [$F(2, 3125) = 10.2$, $p < .0001$]. 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: $F(1, 2647) = 8.9$, $p < .01$; children vs. infants: $F(1, 1249) = 1.6$, $p = .21$; Fig. 3B]. 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 et al., 2009) .

Figure 3

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 towards the mean of all previous saturation levels in predicting participants' choice). Error bars denote 95% confidence interval. *$p < 0.05$, **$p < 0.01$, ***$p < 0.0001$.

Another planned analysis explored participants' performance on the equal-saturation trials where there was no physical difference between the stimuli (20% of the trials). We included these equal-saturation trials to test whether contraction bias would lead to different performance for trials that had low saturation compared to trials that had high saturation. When stimuli on equal-saturation trials had lower saturation, we expected participants to be more likely to fixate the first pinwheel, because greater decay in their memory for the first pinwheel would lead them to remember it as closer to the mean, i.e., more saturated. Likewise, when stimuli had higher saturation, we expected participants to perceive the second pinwheel as more saturated because their memory of the earlier-presented first stimuli would be closer to the mean, i.e., less saturated. Consistent with this idea, we found a numerical but not statistical difference. That is, the equal-saturation trials on which the participants chose the first pinwheel had a lower saturation level than those where participants chose the second pinwheel, but this effect did not reach significance [infants: $t(23) = 0.1$, *n.s.*; children: $t(23) = 0.2$, *n.s.*; adults: $t(23) = 0.4$, *n.s.*; all groups: $t(71) = 0.4$, *n.s.*], perhaps because of the limited number of trials.

Discussion

Using an identical task with one-year-old infants, five-year-old children, and young adults, we examined the influence of prior visual experience on visual perception. We found that all age groups, including infants, showed a contraction bias, where their perception was skewed toward the mean of all previously-experienced exemplars. In addition, we found that this bias increased with age, revealing that adults weighted their memory of prior events more heavily when making 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, memory begins to influence perception in infancy, but exerts a larger 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 non-exclusive possibilities: infants and children may have had weaker representations of prior visual events, *or* they may have weighted their past experience less, instead focusing on in-the-moment saturation levels. Indeed, infants and children were more accurate than adults in selecting the more saturated pinwheel. 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 not sufficient to facilitate percpetual improvement (Reetzke et al., 2016; Vernetti et al., 2017). Regardless, the performance of younger participants suggests that their in-the-moment visual perception was more precise and that they experienced less interference from their past experience, leading to more accurate performance than adults. The data suggest that 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 or capacity shape perception. That is, prior information, which here was built up from trial to trial, may be less available to infants and children compared to adults. 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 et al., 1999; Vöhringer et al., 2018), but there is consensus that infants can build knowledge across sequentially presented stimuli (e.g., Lew-Williams & Saffran, 2012; Maye et al., 2002; Thiessen & Saffran, 2007) and that the ability to retain information over longer periods improves with age and experience (Beckner et al., 2020; Gathercole et al., 2004; Simmering, 2016). It could be that younger learners retain weaker representations of previously-experienced exemplars, such that early events have reduced influence on their perception. Combining our behavioral task with neuroimaging methods that track the accumulation of information from trial to trial (Jaffe-Dax et al., 2018; Lu et al., 1992) could shed light on this potential explanation. Specifically, if infants and children showed a shorter timescale of neural adaptation compared to adults, then this would suggest that their accumulation of information from trial to trial is weaker. A second possibility is that infants and children do accumulate adult-like knowledge of their perceptual experiences, but underestimate its relevance to their current observation. That is, they may have access to relevant information in memory, but they do not incorporate this longer timescale into their in-the-moment decision (Decker et al., 2016). Regardless of the mechanism, we show here that younger participants were more likely than adults to treat individual trials as discrete events, rather than as contingent on the distribution of previously presented stimuli. This suggests more efficient adaptation to (or more emphasis on) newly perceived events in infancy and childhood compared to adulthood.

Across any number of domains, it has been suggested that immaturity can confer certain 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 may be more successful learners than adults. In one prominent example, Newport (1990) argues that children's advantage in learning new languages is in part attributable to their poor implicit memory, such that reduced memory for long sequences of speech enables sensitivity to relations among individual units. Evidence for this general idea comes from both behavioral studies and computational models demonstrating that limits on memory can sometimes support learning (e.g., Cochran et al., 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 the scope of future learning (Lew-Williams & Saffran, 2012; Potter et al., 2017; Thiessen & Saffran, 2007). That is, through experience, learning can become more constrained (Zettersten et al., 2020), and weaker perceptual biases may allow infants and young children to be more receptive to learning from unfamiliar and unexpected events. Infants and young children are able to rapidly incorporate 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 over time. Through experience, infants become less beholden to current sensory input and instead rely on their prior experience to guide their sensitivity to incoming input (e.g., Bar-Haim et al., 2006; Gottlieb, 1976; Pascalis et al., 2002; Werker & Tees, 1984). Our findings suggest that over development, humans learn to integrate their experiences across increasingly longer spans of time, which has 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 delays or disorders, such as ASD). Second, we found a rare case where infants and children outperform adults in a cognitive task. Other cases where younger participants outperform more 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 et al., 2014; Sloutsky & Fisher, 2004) or based on history of exposure (e.g., Kuhl et al., 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.

Conclusion

Contemporary developmental science emphasizes the complexity of infants' early environments and attempts to explain how infants contend with noisy input across a variety of domains (e.g., Bergelson et al., 2019; Clerkin et al., 2017). While adults may be able to rely on their past experience to overcome noise in the input when making perceptual judgments (Raviv et al., 2012), infants and children do not have the same quantity of 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 – using an identical task with infants, children, and adults – 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.

Method

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: 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). 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 [removed for blind review] 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). We excluded trials where the participant took longer than 1 s to make a choice (infants: 29.3 ± 11.6, children: 41.8 ± 10.2, adults: 22 ± 13; mean % of excluded trials ± STD). We attributed these slow responses to technical measurement error or inattentiveness. Delaying the response to the stimuli renders the contraction bias intractable, since the time delay will lead to decay in the representations of both stimuli.

Stimuli and Design

Each trial began with a centrally presented, greyscale attention-getter. 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 there until the participant fixated on it for 300 ms. 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. A second central attention-getter was presented until the participant fixated on it for 300 ms. Two grey 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’.

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

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. 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 ± STD).

Procedure

Participants sat approximately 60 cm from the monitor and eye tracker (Eyelink 1000 Plus, SR Research, Ontario, Canada). The monitor measured 34cm by 27cm and eye gaze was recorded using the 25mm 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 five-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.

Participants were presented a maximum of 105 total trials with incrementally increasing difficulty levels every 10 trials. The saturation (S value for the HSV representation of the image) level of the stimuli was 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]. 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. Infants contributed fewer trials than children, and, in turn, children completed fewer than adults (infants: 29 ± 14.7, children: 58.4 ± 29.9, adults: 101.6 ± 3.8; mean number of completed trials ± STD). This difference in the number of completed trials could have resulted in a less accurate representation of the mean saturation level, which might account for the lower weight of incorporation of that mean estimate into in-the-moment perception. To eliminate this possible confound of the number of trials completed by each group, we performed additional analyses where we excluded all trials beyond the 30th trial for children, and adults alike. Results obtained using this reduced dataset were consistent with the effects reported above (Fig. S1), suggesting that group differences were not due to differences in the number of trials contributed by each age group.

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 6 adult subjects who explicitly linked saturation with the occurrence of the target sound (For example, one of them replied to the second question: “I would look at the brighter pinwheel.”). Excluding these participants from the analysis did not change the reported group differences (Fig. S2), suggesting that these group differences were not due to explicit vs. implicit knowledge about the task, in line with recent work that showed no effect of explicit feedback on contraction bias in perceptual tasks (Loewenstein et al., 2021).

Analysis

We regressed participants' responses in each trial (first look towards '1st' or '2nd' gray place holder) 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).

Acknowledgments

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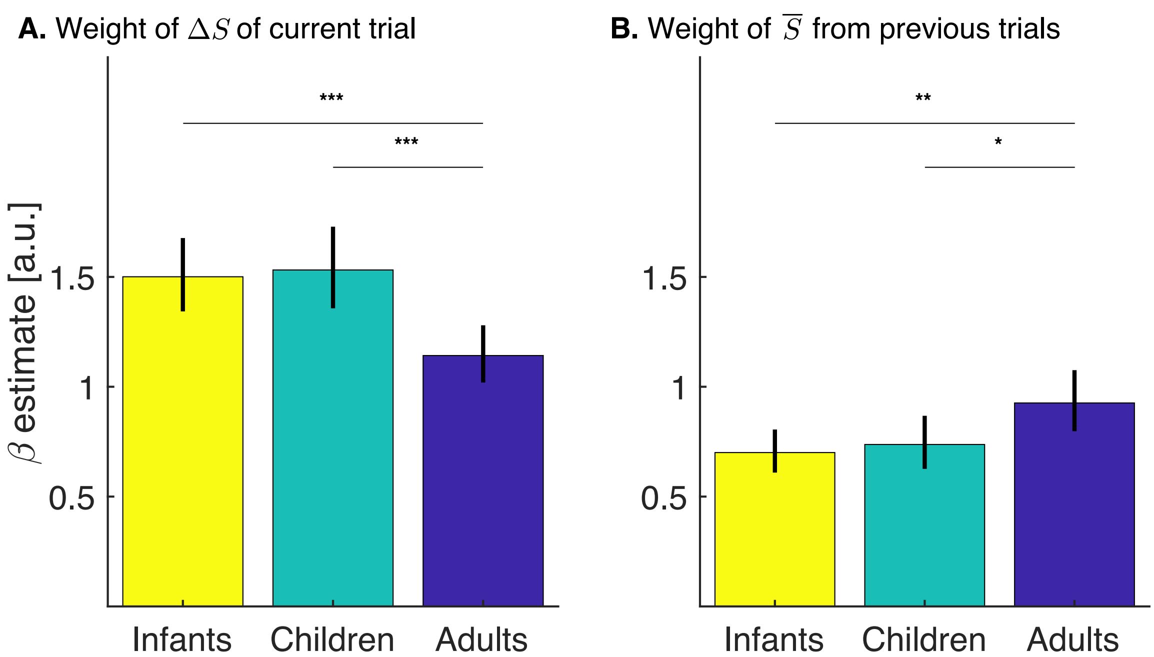
Supplementary information

Figure S1

Weight, by Age Group, of Current Trial (Saturation Difference) and of Previous Trials (Mean Saturation Level) in Predicting Participants' Choices, when average number of analyzed trials is equal for all groups

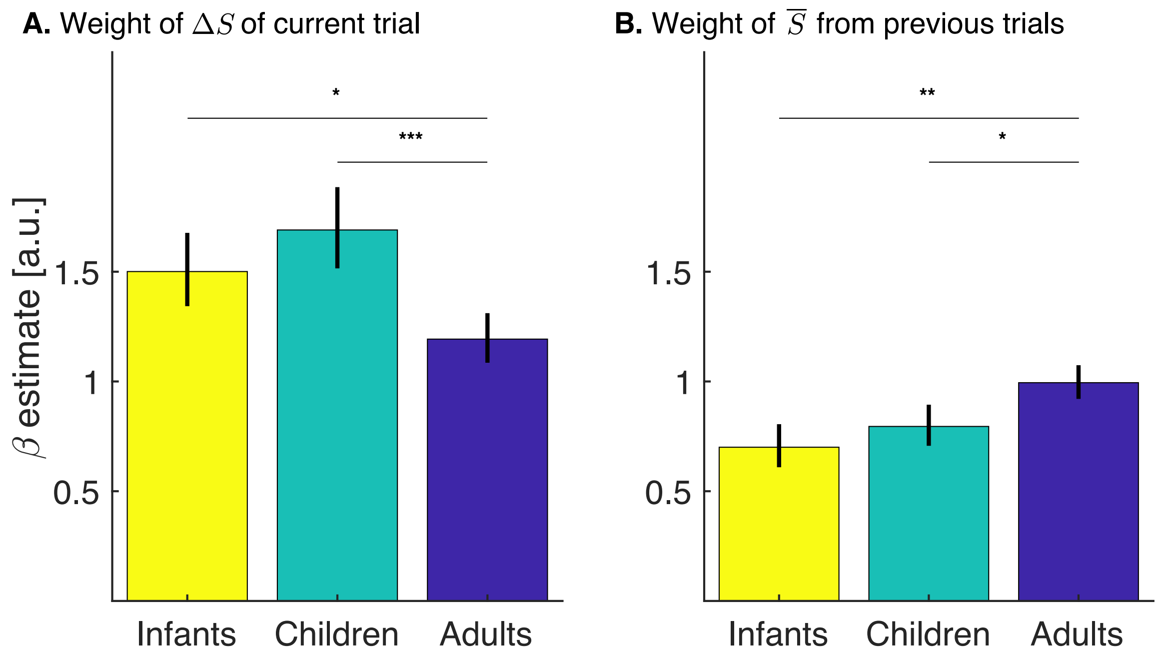


Note. A. Weight of the saturation difference (ΔS) in the current trial in predicting participants' choice. B. Weight of mean saturation level ($\boldsymbol{\overline{S}}$) from previous trials (i.e., merging the representation of the first pinwheel's saturation level in the current trial towards the mean of all previous saturation levels in predicting participants' choice). Error bars denote 95% confidence interval. Average number of trials was 29 for infants. For children and adults, only the first 29 trials were analyzed. *$p <$ 0.05, **$p < 0.01$, ***$p < 0.001$.

After equating for number of trials, we again found that the impact of current observation differed between age groups [$F(2, 1282 = 8.1$, $p < .001$]. Infants and children showed greater influence of current saturation level on their performance on a given trial, relative to adults [adults vs. infants: $F(1, 936) = 11.4$, $p < .001$; adults vs. children: $F(1, 804) = 11.9$, $p < .001$; children vs. infants: $F(1, 824) = .1$, $p = .79$]. We found that the three age groups differed in the impact of previous trials [$F(2, 1282 = 4$, $p < .05$]. Adults showed significantly greater impact of prior compared to infants and children [adults vs. infants: $F(1, 936) = 7.3$, $p < .01$; adults vs. children: $F(1, 804) = 4.1$, $p < .05$; children vs. infants: $F(1, 824) = .3$, $p = .61$].

Figure S2

Weight, by Age Group, of Current Trial (Saturation Difference) and of Previous Trials (Mean Saturation Level) in Predicting Participants' Choices, when adults who had explicit understanding of the task were excluded from analysis and replaced with new participants



Note. A. Weight of the saturation difference (ΔS) in the current trial in predicting participants' choice. B. Weight of mean saturation level ($\bar{\boldsymbol{S}}$) from previous trials (i.e., merging the representation of the first pinwheel's saturation level in the current trial towards the mean of all previous saturation levels in predicting participants' choice). Error bars denote 95% confidence interval. We excluded adults whose answers to the debriefing questions indicated that they had explicit understanding of the task and replaced them with new participants to reach 24 subjects. *$p < .01$, **$p < .0001$, ***$p < 10^{-5}$.

After excluding participants who reported explicitly understanding of the task, we found that the impact of current observation differed between age groups [$F(2, 3128) = 11.8$, $p < 10^{-5}$]. Infants and children showed greater influence of current saturation level on their performance on a given trial, relative to adults [adults vs. infants: $F(1, 2357) = 9.1$, $p < .01$; adults vs. children: $F(1, 2650) = 21.7$, $p < 10^{-5}$; children vs. infants: *same as original analysis*]. We found that the three age groups differed in the impact of previous trials [$F(2, 3128) = 11.6$, $p < 10^{-5}$]. Adults showed significantly greater impact of prior compared to infants and children [adults vs. infants: $F(1, 2357) = 18$, $p < .0001$; adults vs. children: $F(1, 2650) = 10.7$, $p < .01$; children vs. infants: *same as original analysis*].