Memory integration into visual perception in infancy, childhood, and adulthood

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Abstract

We compared the influence of prior knowledge on visual perception in infants, children, and adults in order to explore the developmental trajectory by which prior knowledge is integrated with new sensory input. Using an identical task across age groups, we tested how participants' accumulated experience affected their ability to judge the relative saturation levels within a pair of sequentially-presented stimuli. We found that infants and children, relative to adults, showed greater influence of the current observation and reduced influence of memory in their perception. In fact, infants and children outperformed adults in discriminating between different levels of saturation, and their performance was less biased by previously-experienced exemplars. Thus, the development of perceptual integration of memory leads to less precise discrimination in the moment, but allows observers to make use of their prior experience in interpreting a complex sensory environment.

Keywords: visual perception; implicit memory; contraction bias

Introduction

To make sense of their input, observers do not merely rely on their current observations to perceive, but they also integrate prior knowledge (Hollingworth, 1910; Woodrow, 1933). Integration of prior knowledge allows for overcoming unreliable representation of current observations by combining an additional source of information (Bayesian inference). Differences in reliance on prior experience have been linked to perceptual differences between neurotypical and atypical populations (e.g., Jaffe-Dax, Lieder, Biron, & Ahissar, 2016; Lieder et al., 2019), underscoring the importance of these integration processes. Incorporating prior knowledge allows the perceiver to overcome noise in the environment (e.g., Raviv, Ahissar, & Loewenstein, 2012), but this integration requires the ability to retain detailed information in memory and weigh it appropriately. More recent events are weighed most heavily, and the influence of prior events decays exponentially (e.g., Fischer & Whitney, 2014; Lu, Williamson, & Kaufman, 1992; Raviv et al., 2012). For individuals with weaker implicit memory, this decay may occur more quickly, leading them to rely less on their accumulated experience (Jaffe-Dax, Frenkel, & Ahissar, 2017). Given that children's memory skills develop gradually (e.g., Gathercole, Pickering, Ambridge, & Wearing, 2004), 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 these cognitive capacities for infants, children, and adults in comparable ways, or to use the same task across different age groups. We therefore developed a task that is (1) intuitive (needing no explicit instructions), (2) does not require extensive training (allowing us to exploit informative measures given the small number of trials that are typically attained from infants), and (3) measures the role of memory independently from overall task performance (which can be expected to differ across the age groups).

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 (e.g., Fiser & Aslin, 2002a, 2002b; Jost, Conway, Purdy, Walk, & Hendricks, 2015; Kirkham, Slemmer, & Johnson, 2002; Turk-Browne, Scholl, Chun, & Johnson, 2008). Likewise, there is robust evidence that adults can extract a summary representation of a group of objects that allows them to estimate the average across features including size, brightness, and color (e.g., 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 (e.g., Chong & Treisman, 2003), and recent studies suggest that infants and young children learn visual summary statistics similarly to adults (Balas, 2017; Zosh, Halberda, & Feigenson, 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 (e.g., Brady & Alvarez, 2011). 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 remembering the items that they have previously seen, will show similar biases in their perception. We expected infants and children to less reliably retain the information of the stimuli to-be-compared. We therefore expected that younger participants would show less influence of memory in their perception. One possibility was that we would see gradual increases in the use of prior knowledge through development, and that we would see children weight prior experience more heavily than infants. Another possibility was that we would only see those participants with the greatest memory capacity (adults) showing significant reliance on prior information. However, an alternative possibility was that due to their weaker sensory capacities (i.e., representation of current input), infants and children might integrate prior information with a higher weight as a compensation.

In the current study, we investigated the impact of prior knowledge on visual perception in infants, children and adults by using the same task across all age groups. We tested how participants' accumulated experience with the task would affect their ability to judge the relative saturation levels within a pair of sequentially-presented stimuli. Our hypothesis was that prior experience would bias perception for all participants. This bias, often termed "contraction bias", posits that we perceive events as closer to the central tendency of previous events of the same type (Hollingworth, 1910; Woodrow, 1933). In our experiment, this bias would lead each stimulus to be judged 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 recent perceptual experience.

Method

To assess the influence of prior knowledge on visual perception, we designed an infant-friendly eye-tracking task that made use of the fact that humans, from early infancy, without training, are drawn to look at more saturated (vs. less saturated) stimuli (Werner & Wooten, 1979). 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 grey 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 Figure 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: 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). 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), global inattentiveness (2 children), or vision that was not normal or corrected-to-normal (2 adults).

Stimuli & Design

Visual Stimuli

Each trial began with the centrally presented, greyscale attention attractor. Once the participant fixated on the attractor 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 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 attention attractor was presented until the participant fixated on it for 300 ms. Two grey squares were then presented in the same two locations as the two pinwheels. 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'. If this was the more saturated pinwheel, that pinwheel re-appeared in the same location along with a pleasing sound (Fig 1). On 10% of trials, the two pinwheels had the same saturation level ('catch trials'), and participants saw the pinwheel and heard the sound in whichever location they fixated first. 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, they did not mention location on the screen as a meaningful factor.

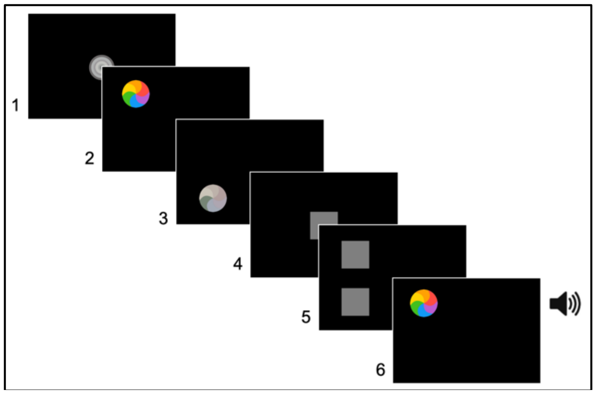


Figure 1: Schematic illustration of trial structure. 1. Participants' gaze was drawn to the center of the screen. 2. The first pinwheel appeared at one of eight possible locations until the participant fixated on it. 3. The second pinwheel appeared at a different location until the participant fixated 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.

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 plus experimenting computer were in front of the experimenter. 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 blinding them to the content of the individual trials (i.e., to prevent biasing of infant 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 incrementing difficulty level every 10 trials. Infants completed 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 current 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. Excluding these trials from analysis equated the average number of completed trials across all groups of participants. Results obtained using this reduced dataset that included only the first 29 trials were consistent with the effects reported below, suggesting that group differences were not due to differences in the number of trials contributed by each age group.

After completion of 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. Excluding these participants from the analysis did not change the reported group differences, suggesting that these group differences were not due to explicit vs. implicit knowledge about the task.

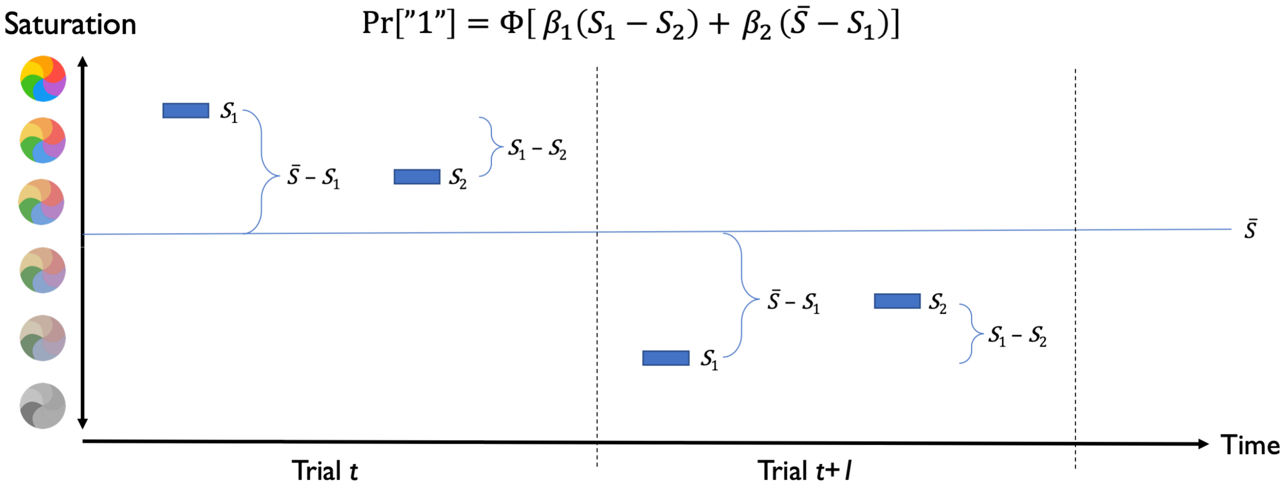


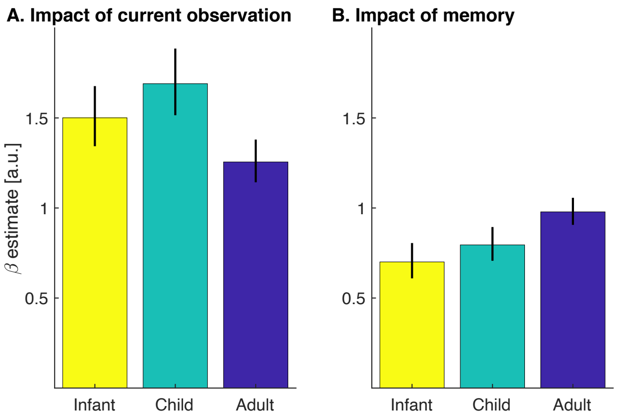
Figure 2: Definition of predictors for participants' choices, illustrating trials with stimuli whose saturation is above and below the mean of all previous trials. β_1 captures the weight of the current saturation difference between the two stimuli in the current trial (roughly the slope of the psychometric curve as a function of saturation difference). β_2 captures the weight of integration of previous stimuli in the current observation (impact of memory).

Results

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, Ahissar, & Loewenstein, 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., its information is less accessible), thus its contraction towards the mean (memory) is greater. 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*. Namely, $\langle \log(s) \rangle_t = \frac{1}{2(t-1)} \sum_{i=1}^{t-1} [\log(s_i^1) + \log(s_i^2)]$. This predictor represents perceptual contraction towards central tendency of the first pinwheel, or summary statistical learning (Hollingworth, 1910; Woodrow, 1933; See Figure 2).

We regressed each individual's probability to fixate on the first-presented pinwheel using these two predictors to measure the relative contributions of perception and memory 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, so simply reporting accuracy would be misleading. Moreover, on the 10% of 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 towards 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. 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 current saturation level on their performance on a given trial, relative to adults (see Figure 3A). That is, adults were actually less likely than infants and children to fixate on the place-holder of the more saturated pinwheel within a pair. We also found that the three age groups differed in the weight of the memory predictor [F(2,3125) = 10.2, $p < .0001$]. While all groups showed a significant effect of memory, adults showed significantly greater bias from their aggregate prior experience (toward the mean saturation of all preceding trials) compared to infants and children (see Figure 3B).


A. Impact of current observation

B. Impact of memory

Figure 3. Weights, by age group, of current observation (saturation difference) and impact of memory. A. Weight of the saturation difference in the current trial *t* in predicting participants' choice. B. Weight of memory integration (i.e., merging the representation of the first pinwheel's saturation level in the current trial *t* towards the mean of all previous saturation levels in prediction participants' choice. Error bars denote 95% confidence interval

Another planned analysis explored participants' performance on the catch trials where there was no physical difference between the stimuli. We used these catch trials to test whether contraction bias, due to greater decay of the representation of the first pinwheel, would lead to different performance for catch trials that have high saturation compared to trials that have low saturation. That is, when stimuli on catch trials have low saturation, we expect participants to be more likely to fixate on the first pinwheel, and when stimuli are more saturated, we expect participants to perceive the second pinwheel as more saturated. Consistent with this idea, we found that the catch trials on which the participants chose the first pinwheel had a lower saturation level than catch trials where participants chose the second pinwheel, but this effect did not reach significance [all *t*'s < 1.6, all *p*'s > 0.1], perhaps because of the limited number of trials.

Discussion

Using an identical task across three distinct age groups, we examined the influence of prior knowledge on 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 can influence perception across ages starting in infancy, but exerts a larger influence with development.

While one construal of our results is that younger participants were less able to incorporate memory into their perception, an important way to interpret these data is to recognize that infants and children were more accurate in selecting the more saturated pinwheel. It may be that they had weaker representations of prior events, or that they weighted their past experience less. It is also possible that infants and children were more motivated by the desire to hear the rewarding sound. In any case, their performance suggests that their visual perception was more precise and that they experienced less interference from their past experience. Their immature memory and reduced integration of prior knowledge may directly or indirectly enhance the acuity of in-the-moment visual discrimination.

Across any number of domains, it has been suggested that immaturity can confer benefits (e.g., Bjorklund, 1997; Turkewitz & Kenny, 1982), and weaker memory skills in particular have been suggested to contribute to cases where children may be more successful learners than adults. In particular, Newport (1990) argues that children's advantage in learning new languages is attributable to their poor implicit memory. She suggests that because children struggle to remember long sequences of speech in their entirety, they become more sensitive to the relations among individual elements, which in turn allows them to master the regularities and structures of the language. Evidence for this perspective comes from both behavioral studies and computational models demonstrating that limits on memory can support learning (e.g., Cochran, McDonald, & Parault, 1999; Elman, 1993; Frank & Gibson, 2011; Kareev, 1995).

Thus, the development of perceptual integration of memory leads to less precise perception in the moment. This may be comparable to phenomena such as perceptual narrowing in that cognitive development is marked by a changing interaction between accumulated experience and current observation. Through experience, infants become less beholden to current sensory input and instead rely on their prior experience to dictate the contrasts to which they are most sensitive (e.g., (Bar-Haim, Ziv, Lamy, & Hodes, 2006; Gottlieb, 1976; Pascalis, de Haan, & Nelson, 2002; Werker & Tees, 1984).

Our findings suggest that children, across the first years of life, learn to integrate their experiences across increasingly longer spans of time, enabling more precise predictions about new observations. It has been suggested that poor reading skills in adulthood are associated with shorter windows of perceptual integration in memory (Jaffe-Dax et al., 2017). Thus, the protracted development of integrating prior perceptual information in forming predictions may contribute to widely observed age-related differences that characterize the process of learning to read.

Methodologically, our current study makes two novel contributions: First, we developed a task that does not require training, explicit instructions, or any verbal skills, thus it can be administered to various age groups – potentially including clinical populations (e.g., minimally verbal individuals). Second, we found a rare case where infants and children outperform adults in a cognitive task.

Why did we observe age-related differences in our perceptual task? First, participants' performance may be explained by changes in memory span or capacity. That is, prior information, which can be accumulated from trial to trial, may be notably 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, Hartshorn, & DiRubbo, 1999; Vöhringer et al., 2018), but there is consensus that the ability to retain information over longer periods does improve with age and experience (Beckner et al., 2020; Gathercole et al., 2004; Simmering, 2016). Second, it could be that younger learners retain weaker representations of previously-experienced exemplars, leading early events to have less influence on their perception. Combining this 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 alternative explanation. A third possibility is that infants overestimate environmental volatility and thus underestimate the relevance of their prior accumulated experience to their current observation. In our study, infants might have perceived each trial as an individual and unique event in isolation from its context. Thus, they considered less accumulated information from previous trials when they perceived the currently presented stimuli. If this is the case, then our findings suggest faster adaptation to newly perceived events in infancy and childhood compared to adulthood.

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