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

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

Abbriviated title: Memory shapes perception from infancy

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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

Significance Statement

This research examines human perception in a dynamic way that highlights interacting systems. While perception and memory — two core domains of cognition — are often studied separately, it has become increasingly clear that they should not be. Our study shows that memory shapes perception in infants and across the lifespan. To study this, we developed a task that can be used identically with 1-year-olds, 5-year-olds, and adults, where participants implicitly judge the relative saturation levels within pairs of sequentially-presented stimuli. Infants in this task were more accurate than adults, which is explained by adults' increased reliance on visual memory. The findings suggest that changes in how humans weigh current input against prior experience contribute to age-related changes in perception, across many domains.

Introduction

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 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 et al., 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 et al., 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 et al.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 et al., 2017). Children, of course, have less experience than adults and more limited memory (Gathercole et al., 2004). 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. 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 enable direct comparison across ages, we developed a perceptual judgement task that is (1) intuitive, with no need for explicit instruction, and (2) does not require extensive training, allowing for 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, 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 summary representations of a group of objects that allows them to estimate averages 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 high accuracy (Chong & Treisman, 2003; Piazza et al., 2013), and recent studies suggest that infants and children also learn visual summary statistics (Balas, 2017; Zosh et al., 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 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 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 similar influence on infants', children's, and adults' visual perception.

Methods

Our study investigated the impact of prior knowledge on visual perception in infants, children, and adults, using the same task across age groups. To explore the role of prior experience in 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). 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).

Using this task, 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. Specifically, 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.

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). 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).

Experimental Design

Each trial began with a neutral grey-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 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 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'. 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. Figure 1 depicts a schematic illustration 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. The saturation levels – defined as the S value in the HSV (Hue, Saturation, Value) representation of the image – of one of the stimuli were 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. 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 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 the target location, at which time they saw the pinwheel reappear and heard the rewarding sound. Trials ended after 4 seconds 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 ± STD).

Procedure

All 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.

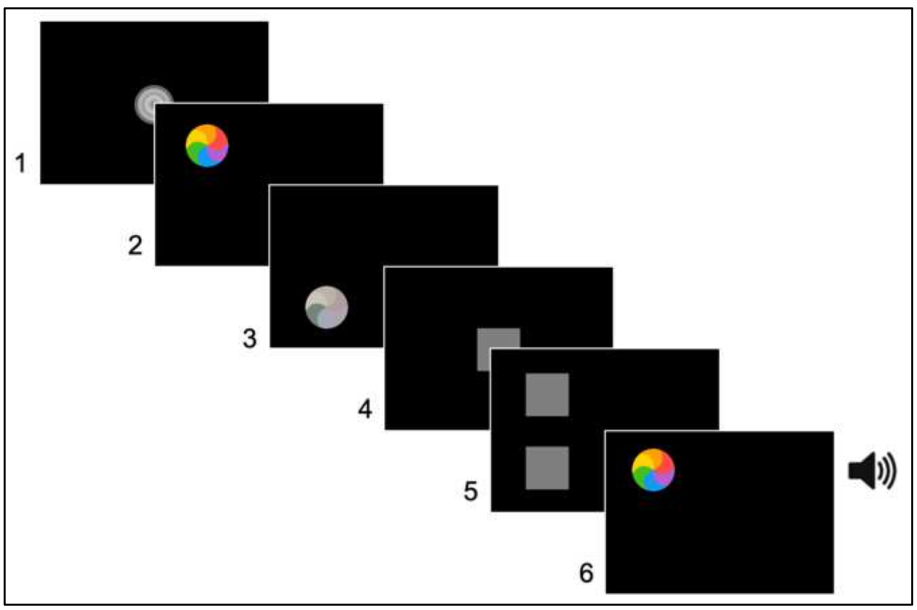
Infants sat on their caregivers' laps throughout the experiment. Caregivers were instructed to not interfere with the infant and wore a visor during the experiment, which prevented them from seeing the screen and blinded them to the content of the individual trials, to avoid biasing the infants' behavior. 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. In order to equate the conditions across age groups, no instructions were given and no explicit feedback was provided.

Participants were presented 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 ± 14.7, children: 58.4 ± 29.9, adults: 101.6 ± 3.8; mean number of completed trials ± 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 vs. 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 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." See Fig 3-2 in Extended Data for complete report of participants' answers). Excluding these participants from the analysis did not change the reported group differences (Fig. 3-2 in Extended Data), 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).

Figure 1

Schematic Illustration of Trial Structure



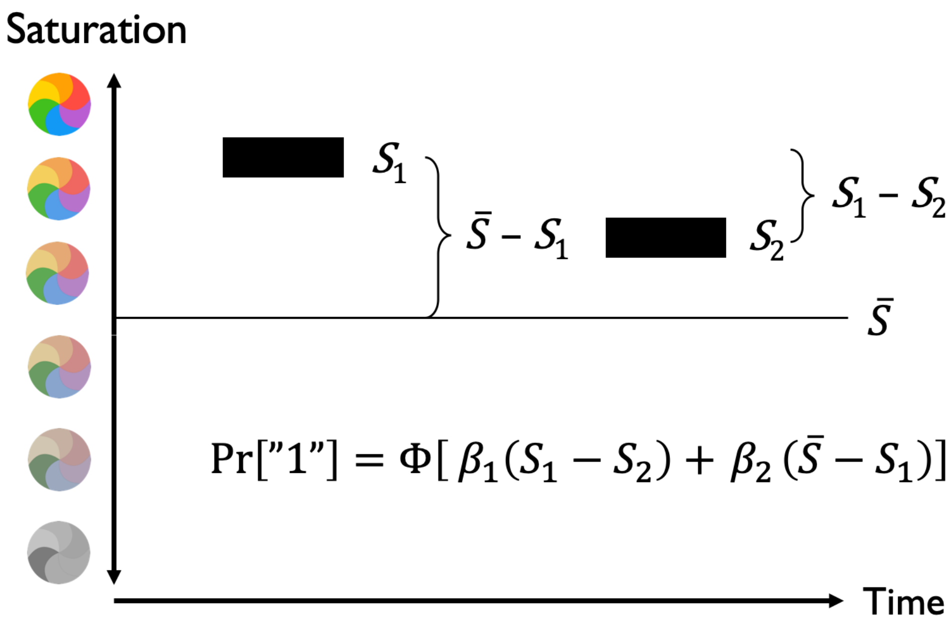
Note. 1. Participants' gaze was drawn to the center of the screen with a grey scale attractor. 2. First, a pinwheel appeared in one of eight possible locations until the participant fixated on it. 3. A second pinwheel appeared at a different location until the participant fixated on it. 4. Participants' 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.

Statistical Analysis

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 either 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. 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 (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: $\langle \log(s) \rangle_t = \frac{1}{2(t-1)} \sum_{i=1}^{t-1} \left[\log\left(s_i^1\right) + \log\left(s_i^2\right) \right]$. 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 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 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.

Code and Data Accessibility

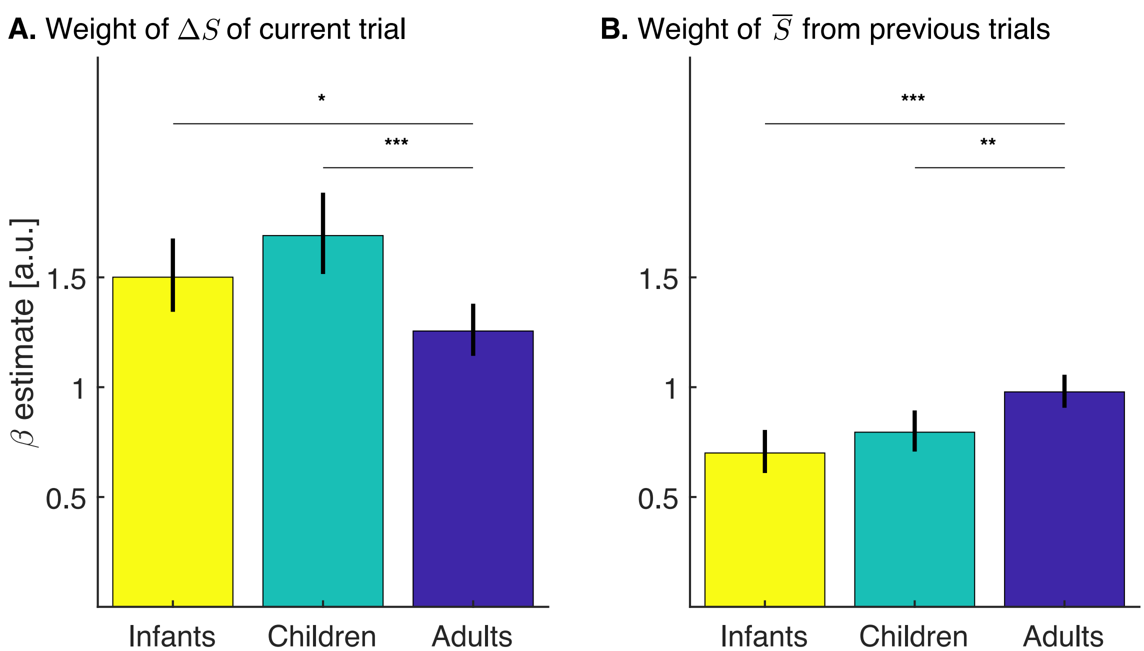
Original code and data are available at: https://osf.io/xvk5e/?view_only=bc4eb4df06be412995757df29e117f83

Results

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' grey 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). 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%), suggesting that infants' children's and adults' preference was automatically drawn toward pinwheels of greater saturation. 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 [$F(2, 3125) = 8.4$, $p < .001$, $\eta_p^2 = 0.05$, $Cohen's\ d = 0.45$]. 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. 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).

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. *$p < 0.05$, **$p < 0.01$, ***$p < 0.0001$. These results were also replicated when the average number of trials for each group was kept equal (Fig. 3-1 in Extended Data) and when adult subjects who reported explicit understanding of the task were excluded from analysis (Fig. 3-2 in Extended Data).

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: $F(1, 2647) = 8.9$, $p < .01$; 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).

Differences 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 all participants. Results obtained using this reduced dataset were consistent with the effects reported above (Fig. 3-1 in Extended Data), suggesting that group differences were not due to differences in the number of trials contributed by each age group. Using this smaller dataset, we were also able to compare accuracy (percent correct) between the groups. In line with our main regression analysis, infants and children showed higher accuracy on their first 29 trials than adults [infants: 70.1 ± 13.5, children: 74.3 ± 15.1, adults: 56.2 ± 15.9; mean % accuracy ± STD; $F(1,70) = 9.4$, $p < 0.005$)].

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. Supporting 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 groups, including infants, 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 non-exclusive 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 percepetual 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 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 et al., 1999; Vöhringer et al., 2018), but there is consensus that infants build knowledge across sequentially-presented stimuli (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). 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 et al., 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. 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 et al., 2016). 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 vs. 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 learn more successfully than adults. For instance, Newport (1990) argues that children's advantage in learning language is in part attributable to their poor implicit 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 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 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 children to be more receptive to learning from unexpected events. Infants and young children 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. 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 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 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 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 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 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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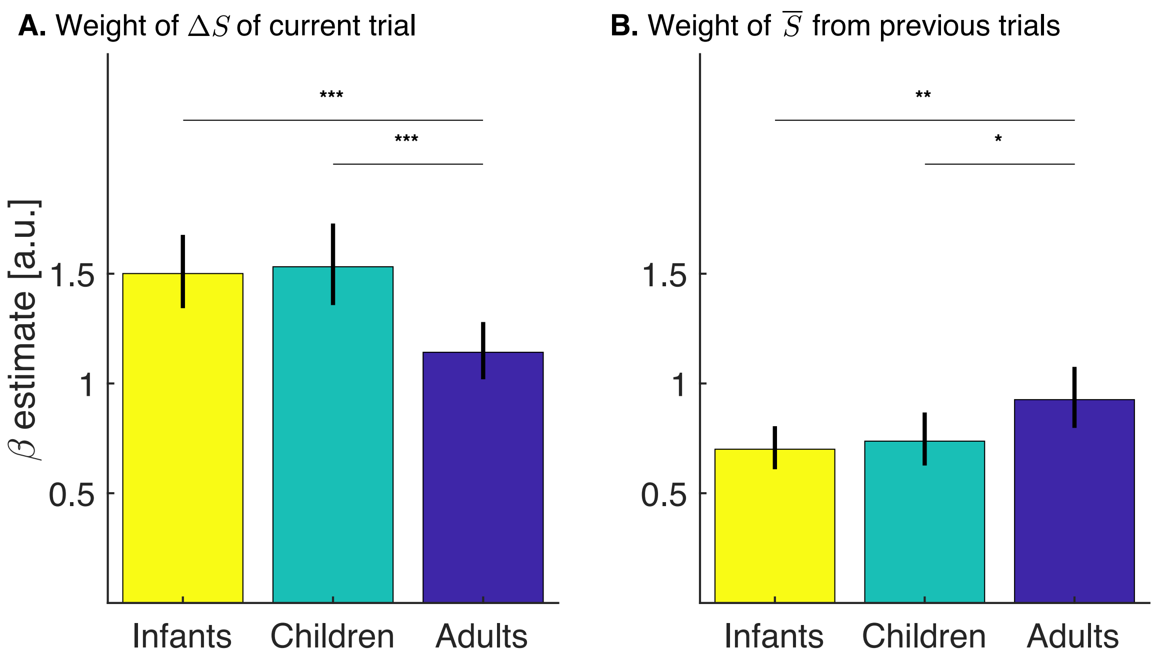
Extended Data

Figure 3-1

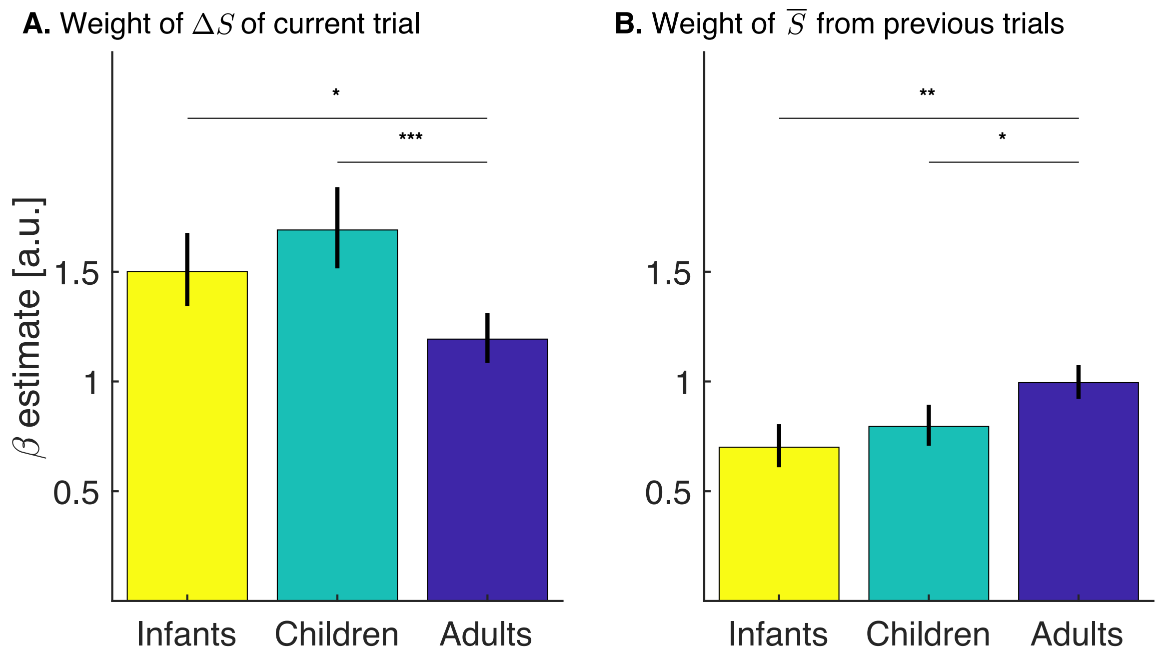
Weight, by Age Group, of Current Trial (Saturation Difference) and of Previous Trials (Mean Saturation Level) in Predicting Participants' Choices, when average number of analyzed trials is equal for all groups



Note. A. Weight of the saturation difference (ΔS) in the current trial in predicting participants' choice. B. Weight of mean saturation level ($\overline{\boldsymbol{S}}$) 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. 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 3-2

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 ($\overline{\boldsymbol{S}}$) 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 < 0.01, **p < 0.0001, ***$p < 10^{-5}$. After excluding participants who reported explicitly understanding of the task, we found that the impact of current observation differed between age groups [$F(2, 3068) = 15.6$, $p < 10^{-5}$]. Infants and children showed greater influence of current saturation level on their performance on a given trial, relative to adults [adults vs. infants: $F(1, 2297) = 13.2$, $p < 0.01$; adults vs. children: $F(1, 2590) = 28$, $p < 10^{-5}$; children vs. infants: *same as original analysis*]. We found that the three age groups differed in the impact of previous trials [$F(2, 3068) = 10.8$, $p < 0.0001$]. Adults showed significantly greater impact of prior compared to infants and children [adults vs. infants: $F(1, 2297) = 17.2$, $p < 0.0001$; adults vs. children: $F(1, 2590) = 9.7$, $p < 0.01$; children vs. infants: *same as original analysis*].

Qualitative Data

In the debriefing stage, each adult subject answered four questions:

1. What do 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?

Below we share notes of individual participants' responses to each question:

<u>Subject 1</u>

1. Predicting what will come next; reacting to different kinds of colors and shapes (some circles were more vibrant than others); appeared in different locations.
2. At first, I looked in the general direction and looked in between them; then I thought higher square first and then lower square; and then left square to right square.
3. When the colorful circle was on the screen.
4. My gaze was moving to the next thing; the squares appeared in the location where the circles were.

<u>Subject 2</u>

1. How attracted are you to certain stimuli and the brightness of it.
2. I didn't realize there was a pattern at first; then I started doing the first dot that came up (I would look in that direction when the squares came).
3. When I looked at the correct square (the correct square was the one when the circle came up after I looked at it).
4. There were bright and dull colors; sometimes the pattern that I was using was wrong; the squares appeared in the same place as where the circles previously were.

Subject 3

1. Expectation.
2. I looked at the square where the circle first appeared; if it didn't pop then I looked at the other one.
3. After the square popped and became a circle.
4. Nothing.

Subject 4

1. To see if you can predict where the pinwheel is when it's under the box.
2. For the first couple ones, I didn't know the purpose of the boxes and then I realized the pinwheel was under them; I usually looked to the box where the pinwheel was last but sometimes it wasn't in that spot.
3. Whenever the pinwheel was revealed under the box once you found it.
4. There were different sounds, but I don't know if they correlated to anything; some of the pinwheels were more faded than others.

Subject 5

1. Predictions.
2. For the most part it seemed that the less saturated the pinwheel was, the more likely the pinwheel was to be the first to appear on the screen; if the pinwheel was more saturated, it was more likely that the pinwheel was going to be the second to appear on the screen; if there were two desaturated pinwheels, I looked to where the first pinwheel appeared.
3. After the box was revealed; after I looked at the correct box.
4. There might have been a correlation with the sound, but I don't think there was; I paid more attention to location of pinwheel than I did to sound.

Subject 6

1. Decision making.
2. I tried to figure out which one would uncover the circle; it felt random; I couldn't really figure it out.
3. Every time (trial).

4. There were brighter circles and lighter circles; the two white squares would appear at the same locations of the circles.

Subject 7 – **This subject was excluded in Fig. 3-2 for explicit understanding of the task.**

1. Looking at the more colorful image; study about attention and how colors attract attention; how well do we differentiate colors; for many of them I wasn't sure which one was more colorful.
2. I looked at the square that had the more colorful circle; when I looked at the other one nothing happened.
3. Whenever I got the right answer; they were very different sounds.
4. There might have been a bias to the order; the first one that appeared seemed more often to be the brighter one; sometimes I thought it was weird that I had to go to the center (my eyes just wanted to directly go to the square that I knew was going to cover the brighter circle).

Subject 8 – **This subject was excluded in Fig. 3-2 for explicit understanding of the task.**

1. Assessing color recognition in infants and comparing it to adults; pattern recognition.
2. At first, I couldn't figure it out; at some point I noticed that the white squares were where the beach balls were, and then changed to the ball that was previously the brighter color.
3. When the squares revealed the beach ball.
4. The white squares always revealed the location of the one that had the more saturated color; the eyetracker recognized when I shifted my gaze to the more saturated one.

Subject 9

1. Focusing.
2. I just kind of waited for one of them to get the circle back on; I started with the top and go to the bottom.
3. When the boxes left, and the circles came back.
4. There was a colorful pinwheel, the boxes were white.

Subject 10

1. Tracking where your eye goes to either of the two squares after being influenced by the other great.
2. No strategy; probably influenced by whatever was before (for that trial).
3. In the beginning of each trial.

4. Didn't notice any patterns; the order of the circle then square then circle was the same from trial to trial.

<u>Subject 11</u>

1. looking at which box you look at first.
2. I kind of did it how I would read like a book (left to right; up to down); spatially.
3. After one of the boxes turned into a beach ball.
4. There was a set pattern of dartboard, two beach balls, dartboard, and then two boxes and then one would turn into a beach ball and then a sound; some beach balls were very brightly colored; sometimes the colors were more chrome (I don't know when one appeared over the other).

<u>Subject 12</u>

1. If I could guess which circle was under the box; at first, I thought there was a pattern that I was supposed to figure out but then sometimes I got it wrong.
2. It just felt intuitive; I thought there was a pattern, but I just let my eyes go where I felt like they should go.
3. After I got it right, but I can't remember if it was every time.
4. Some of the circles were more faded colors and some were brighter.

<u>Subject 13</u> – **This subject was excluded in Fig. 3-2 for explicit understanding of the task.**

1. Something to do with attention; to see if babies vs adults pay more attention to the stimuli.
2. I tried looking at both; at first, I tried to look at both really quickly (no preference of which one came first or second); towards the end I tried to look at both at the same time.
3. When the colorful circle came out (not all of them but couldn't remember the pattern).
4. The squares were still; the circles moved; there was a difference in color between the circle (some rainbow and some black and white).

<u>Subject 14</u>

1. Seeing where you look (the squares would pop up in the locations of the circles and one was the right one to look at) so maybe which one you look at first.
2. At first, I was just looking to the top and the right ones; sometimes, I felt like I wanted to go left to right like I was reading.

3. After I would get the right square that showed the color wheel.
4. Sometimes the colors of the color wheel weren't as bright (it seemed random).

Subject 15

1. No answer.
2. Initially, I was looking in the middle and then nothing happened; eventually I started going to whichever was furthest from the image that I previously looked at.
3. Whenever it gave the circle after looking at the square.
4. There are different levels of color, but I couldn't find a reason.

Subject 16

1. Babies’ attention having to do with their responsiveness to different stimuli because there were different colors and different shapes.
2. Sometimes, top to bottom and then left to right.
3. When the rainbow spiral was on the screen; when there was a black and white ripple.
4. The two squares were near each other (interested in seeing which one will the baby look at).

Subject 17

1. Attention.
2. I looked at the one at the left first or the top one first.
3. Always after the rainbow pinwheel came after the box.
4. On a couple trials, the rainbow pinwheel was not as colorful (it was dulled out); some trials were faster than others.

Subject 18

1. Tracking how your eyes respond to different color changes.
2. I couldn't tell if you had to look at each one or if you had to widen your field of view/in the middle; I tended to look at one or the other; no preference of which to look at first.
3. After the white squares.
4. Some pinwheels were fainter; I felt at one point that the squares got bigger.

Subject 19

1. How different shapes influence eye movements.
2. I tried to look at both at the same time, if that didn't work then I looked at both individually.
3. At the beginning when there was a target (there was a spring sound).
4. The colors changed from vibrant to more dull; sometimes the swirl was half white.

Subject 20

1. Tracking people's eye movements across the screen; maybe if there were words attached to it.
2. Didn't focus on either; kept them both in my vision as a whole, while focusing on the equidistant point; then I looked towards the next stimulus (rainbow circle that reappeared).
3. Usually when the swirling rainbow circle came up.
4. Varied between up/down and left/right; some have different intensities/hues; some were more faded than others or more richly colored; I don't remember if they made different noises or not.

Subject 21 – **This subject was excluded in Fig. 3-2 for explicit understanding of the task.**

1. Recognizing color and predicting things; tracking eyes to see where you're looking before the circle reappears.
2. If one circle was brighter than the other, I looked at that square; when they were the same color I looked to where the first circle was, but it switched up, so I wasn't sure.
3. After the circle covered by the square was revealed.
4. It showed two spinning pinwheels then cover them both with squares; if there was a color difference it would then show the brighter one.

Subject 22 – **This subject was excluded in Fig. 3-2 for explicit understanding of the task.**

1. Trying to get kids to recognize patterns and when they get the right pattern, then the shape would be revealed.
2. it was based on the rainbow wheel; if it was brighter, I would look to the one that was brighter; if they were the same, I would look at the one that was most recent.
3. After I looked at the right square.

4. They all popped up in the same four places.

<u>Subject 23</u>

1. Speed of eye-movement.
2. I didn't really decide; I just realized that whichever one that had the circle behind was the one that would make the program progress; if I looked at one and nothing happened, I looked at the other one.
3. Whenever I picked the right square and the circle behind it came up.
4. The colors of the spinning wheel varied.

<u>Subject 24</u>

1. Tracking eye movements; having color vs without color.
2. Usually. the top one or the one on the left.
3. Random; usually with a rainbow circle.
4. There was always a gray circle in the middle; a lot of times the squares were right next to each other, on top of each other, or diagonal from each other.

The following subjects were added for Fig 3-2 after excluding the subjects who reported explicit understanding of the task

<u>Subject 25</u>

1. When there were two squares, predicting if we try to look at both.
2. I would look at the top one and then the bottom one.
3. When I looked to the block that ended up turning into a circle.
4. Nothing.

<u>Subject 26</u>

1. Finding a pattern between the circles and what color they are.
2. I tried to find a pattern; I thought maybe the first spinning wheel; I couldn't really find the pattern so then I just looked at both; it helped that I knew where the squares would pop up based on where the circles were.
3. After I discovered the spinning wheel under one of the squares.

4. There was a center dot, then two spinning wheels, then two blank squares, after one of the blank squares was another spinning wheels; I thought there was a correlation between how long it took me to find the wheel and the sound (maybe the better the sound the faster I did but I'm not sure)

<u>Subject 27</u>

1. Unsure.
2. I looked at both; I tried to look at both at the same time; I picked some first, but I couldn't distinguish what the trend was.
3. When something vanishes; when I looked away then maybe that sound ends abruptly,
4. When I looked directly at an object, it vanishes; I just looked to that object then it moved to the next one; some multicolored circles were brighter and some were dimmer

<u>Subject 28</u>

1. Guessing game; trying to guess where the shape is.
2. I don't think I had a method to it; I just kind of looked at whichever worked.
3. Like in a children's game when it plays a sound that you've been defeated (I'm assuming she means when she looked to the incorrect square first).
4. If you didn't look at the right one, it wouldn't change the square to the spinning target; sometimes the pinwheels stopped moving; the pinwheels changed location of direction

<u>Subject 29</u>

1. Attention.
2. I tried to make it so my eyes were equally on both of them.
3. When the really bright pinwheel came up; sometimes the pastel ones made noises too.
4. Before the squares popped up, the black and white target always showed up.