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The Development of Implicit Learning From Infancy to Adulthood: Item Frequencies, Relations, and Cognitive Flexibility

ABSTRACT: *The majority of cognitive processes show measurable change over the lifespan. However, some argue that implicit learning from environmental structure is development invariant [e.g., Muelemans et al. [1998] Experimental Child Psychology, 69, 199–221; Reber [1993] Implicit learning and tacit knowledge: An essay on the cognitive unconscious. Oxford University Press], while others have shown that adults learn faster than children [Thomas et al. [2004] Journal of Cognitive Neuroscience, 16, 1339–1351]. In two experiments, we tested infants through adults using the same saccade latency measure and behavioral learning paradigm. We examined implicit learning when subjects are presented with interleaved regularities acting on one item, as well as the ability to adjust behavior when learned information is violated. In one comparison, the first- (item frequencies) and second- (spatiotemporal item relations) order statistics are in conflict, allowing us to examine flexibility in learning from multiple parameters. Data from Experiment 1 (N = 90, 6- to 30-year olds) showed no developmental differences in either implicit learning from environmental regularity or flexibility of learning from conflicting parameters across our age range. Accuracy data showed that children are especially sensitive to low frequency relative to high frequency items. In Experiment 2, we showed that 7- to 11-month-old infants had a saccade latency profile that was consistent with task structure, that is, they simultaneously learned both item frequencies and spatiotemporal relations, as indicated by data patterns similar to those obtained in Experiment 1. Taken together, these data provide support for developmental invariance in implicit learning from environmental regularities.* © *2012 Wiley Periodicals, Inc.* Dev Psychobiol 54: 664–673, 2012.

Keywords: *infant; learning*

INTRODUCTION

Developmental change relies on the integrity of mechanisms of information uptake, both implicit and explicit. Studies have yielded mixed outcomes with respect to the development of implicit learning, that is learning from experience without intention or awareness (Kartekin, Marcus, & White, 2006; Muelemans, Van der Linden, & Perruchet, 1998; Reber, 1993; Schacter, 1987; Schacter & Graf, 1986; Thomas & Nelson, 2001; Thomas et al., 2004; Vaidya, Huger, Howard, & Howard, 2007). One form of implicit learning involves gathering information from environmental regularity. Sensitivity to regularity and the ability to act both in accord with learned information, and to flexibly adjust behavior when learned regularities are violated, are key to efficient interactions with the environment. As

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a domain-general learning mechanism, this has relevance for a wide array of cognitive skills including motor learning, object perception, and language development to name a few. An item can be regular because it is frequent in occurrence, or because it is frequently presented in relation to other items. This work considers the development of implicit learning from environmental regularities, based on both item frequency of occurrence and relations, as well as the cognitive flexibility required to adjust behavior when both are learned at once. We use oculomotor and manual response measures and from infancy through adulthood.

The task most commonly used to consider implicit learning from regularities in middle childhood and beyond is the serial reaction time task (SRT, originally by Nissen & Bullemer, 1987). In a SRT task, subjects are asked to press buttons that correspond to three or four stimulus locations on the screen. Without subjects' knowledge, the response locations occur in a repeated sequence. Faster response times to this sequence over trial exposure, relative to responses to randomly presented stimuli, are taken as indication of learning (Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Nissen & Bullemer, 1987). Although response times indicate learning, in general subjects do not subsequently report knowledge of the task structure.

Some have argued that implicit learning mechanisms are development invariant (Reber, 1993). Muelemans et al. (1998) tested young children (6–10 years) and adults on a SRT and showed both that learning was similar across the groups and that retention of sequences 1 week later was also the same across groups. Thomas and Nelson (2001) considered younger children 4-, 7-, and 10-year of age on an implicit sequence learning task and found little developmental change in reaction time measures, but found small differences in anticipatory responses to correct locations. Kartekin et al. (2006) used both oculomotor and manual response measures to examine implicit learning in a SRT. They also found no developmental differences in learning for either measure.

Evidence that contradicts the developmental invariance model also exists. Thomas et al. (2004) did find evidence of developmental implicit learning differences in a standard SRT task in combination with functional magnetic resonance imaging data (fMRI). Interestingly, they found involvement of the hippocampus and caudate, structures widely accepted as learning systems, to be engaged in implicit sequence learning, with caudate activity correlating best with learning measures. Notably, Thomas et al. (2004) used a bimanual response method. Others (De Guise & Lassond, 2001) have shown no learning differences in children relative to adolescents in SRT performance under unimanual conditions, but reliable learning differences under bimanual conditions. This suggests that the developmental effect observed by Thomas et al. (2004) may have resulted from learning the visual-motor task requirements above and beyond implicit learning of task sequences. Data from other implicit learning tasks also bears on this issue. In a contextual cueing task, subjects implicitly learn that some configuration of items cues the location of a target in a visual search display (Chun & Jiang, 1998). Implicit learning in this task has been shown to involve the medial temporal lobes (Chun & Phelps, 1999). Using contextual cueing, Vaiydia et al. (2007) showed that magnitude of learning to be greater in adults than in children.

Lacking from this debate is an investigation, using a single paradigm, that spans infancy through adulthood. This comprises the main goal of this work. Amso, Davidson, Johnson, Glover, and Casey (2005) generated an implicit learning task where participants saw centrally-presented stimuli in a continuous sequence. A stimulus can be salient because it is infrequent (Zink, Pagnoni, Martin, Dhamala, & Berns, 2003) or because its occurrence is infrequent or unpredicted in a particular relational context. The choice of these parameters was motivated by an approach to learning first introduced by Cohen, Poldrack, and Eichenbaum (1997). They argued that memory processes are better defined by the mechanisms underlying them, than by their availability to conscious awareness. Declarative memory mechanisms, dependent on hippocampal and parahippocampal regions, act to bind together aspects of items in a compositional and flexible manner. This flexibility of item relations at encoding allows for subsequent generalization (Shohamy & Wagner, 2008). In contrast, procedural memory mechanisms are inflexible and non-relational representations of single items or sequences that may be supported by frontostriatal systems (Cohen et al., 1997; Peigneaux et al., 2000; Rauch et al., 1997). As noted, some of the disparity in the literature on the development of implicit learning comes from tasks that require striatal (SRT) relative to hippocampal (contextual cueing) circuitry. In addition, there is some evidence that the two learning systems are competitive, such that only one supports behavioral response at any given time (Poldrack & Packard, 2003). Therefore, frequency of item occurrences and relational co-occurrence probabilities were statistically manipulated in Amso et al. (2005) such that the two statistics acted in conflict on the same item (high item frequency/low relational probability), allowing us to consider not only learning over trial exposure but the cognitive flexibility inherent in implicit learning from conflicting parameters.

Amso et al. (2005) showed that adult subjects were able to learn and flexibly maintain both parameters, as indicated by faster reaction times to frequently presented relative to infrequent items and co-occurrence relations. Furthermore, the hippocampus was recruited for implicit learning of relational information and the striatum for simple item occurrence repetition frequencies, again as indicated by contrasts between frequent relative to infrequent items and co-occurrence relations. The two learning mechanisms were cooperative in this work, which is inconsistent with some previous data suggesting that they compete during learning (Poldrack & Packard, 2003).

The current work adapted the Amso et al. (2005) task for use across development and to better mirror the implicit learning SRT tasks described. Specifically, centrally presented stimuli predicted the subsequent location and identity of peripheral targets. Responses to novel, relative to familiar, information is used as indication of learning in both saccade latencies to peripheral targets (infants) as well as combined saccade latency/manual response measures (children, adolescents, and adults). Kartekin et al. (2006) have shown consistency across these measures. Flexible integration of environmental structure requires a certain amount of behavioral adjustment. Response to relative, rather than absolute, novelty in our task structure permits consideration of behavioral adjustments that are adaptive to the integration of new information into an existing framework as it becomes available. In an attempt to mirror environmental complexity, this task is designed such that conflicting information is acting on one item (high item frequencies/low relational probabilities), allowing us to ask whether such complexity would itself be a constraint on implicit learning from environmental regularity and serve to change a seemingly invariant developmental course. If implicit learning is indeed development invariant, we would expect the same pattern of behavior across our age groups. Based on Amso et al. (2005), participants would be able to flexibly learn both the item relations and frequency information in concert. However, an alternative would be that item relations (a second-order statistic) are more taxing than simple frequency-based learning and would uniquely show developmental change over the lifespan. A final possibility is that learning each parameter is development invariant but that flexible integration of the two parameters is only possible with development. In that scenario, we would expect that behavior can only be driven by one parameter (relations or frequencies) at any one time in younger subjects.

GENERAL METHODS

Apparatus

Infants were seated in a parent's lap approximately 100 cm from a 50 cm stimulus-presentation monitor. Children, adolescents, and adults sat in the same chair at the same distance from the screen. Manual responses were collected with a standard Dell PC keyboard, using the arrow keys. Eye movement data were collected with a remote optics corneal reflection eye tracker (Applied Science Laboratories Model 6000).

Each subject's point of gaze (POG) was calibrated with an attention-getter that contracted and expanded in synchrony with a rhythmic sound at the top left and bottom right corners of the screen. Subjects then viewed the attention-getter at several random locations on the screen. If the POG was not within $.5^{\circ}$ of the center of the attention-getter at all locations (minimum of 6), the calibration procedure was repeated. The experiment began only once the calibration criterion had been reached. Eye tracking data was collected at 60 Hz, with the software averaging across five samples.

Paradigm

Participants viewed sequentially presented alternating central (cue) and peripheral (target) stimuli on a blue background. Cue duration was 1,000 ms and target stimulus duration was 1,000 ms, with a 500 ms interstimulus interval. It takes an infant approximately 200 ms to program an eye movement (Canfield & Kirkham, 2001), making this more than sufficient time for gaze to be directed toward the target.

There were two centrally presented cues (a cartoon octopus and turtle) that predict both the identity and spatial location (far right, far left, above center, e.g., a cartoon orange fish always appears to the far right of center) of subsequent targets each with varying probabilities (see Tab. 1). Simultaneously, we varied the frequency of occurrence of the target items throughout the task, independent of target co-occurrence relations with cues. Target identity and location were bound in this task and a target always appeared in the same location. Cues were presented with equal probability (50%). Cue 1 predicts Target 1 on 75% of trials, and Target 2 on 25% of trials. Cue 2 predicts Target 1 with a 25% probability, and Target 3 with a 75% probability. Simultaneously, the frequency with which each target item is presented throughout the task varied. Frequency of occurrence for Target 1 is 50% and for Target 2 is 12% over the entire task (see Tab. 1). Target 3 was included to make the controlled parameters numerically possible, but was not intentionally manipulated.

Table 1. Task Conditions, Structure, and Comparisons

Condition	Cue	Predictive Probability	Target Item Frequency
High probability relation/high frequency item (Cue1/Target1)	Turtle (50%)	Orange fish (75%, 39 trials)	Orange fish (50%, 52 trials)
Conflict low probability relation/ high frequency item (Cue 2/Target1)	Octopus (50%)	Orange fish (25%, 13 trials)	Orange fish (50%, 52 trials)
Low probability relation/low frequency item (Cue1/Target 2)	Turtle (50%)	Blue fish (25%, 13 trials)	Blue fish (12.5%, 13 trials)
Filler	Octopus (50%)	Yellow fish (75%, 39 trials)	Yellow fish (37.5%, 39 trials)

Item occurrence frequencies and relational probabilities were statistically manipulated such that the two statistics acted in conflict on the same item (high frequency item/low relational probability), allowing us to consider not only learning over trial exposure but the cognitive flexibility inherent in manipulating two statistics. The Cue2/Target1 combination was the relevant Conflict condition. Relative to Cue1/Target1 (75% pairing, High Probability Relations Condition), the Cue2/Target1 Conflict pairing is low in relational probability (25%) but identical in simple frequency of item occurrence weights. In comparison to the Cue1/Target2 (Low Item Frequency Condition) pairing, the Conflict condition is equal in relational probabilities (25%), but not frequency of simple item occurrence (Target 1 = 50%, Target 2 = 12%) weights (see Tab. 1).

There were 106 cue-target pairs in the task. Rather than use one or two novel test stimuli after exposure is complete to indicate longer response and therefore learning, we examined response latencies on every trial and ultimately averaged the data into four binned intervals (trials 1–26, 27–52, 53–78, and 79–104), with number of trials roughly equally distributed across each bin. The binning allowed us an opportunity to examine the timing of the shift to faster response latencies to high relative to low probability relations and high relative to low frequency items. Each central cue was accompanied by a sound (“Ding” for Cue 1, and “Dong” for Cue 2) to return subjects’ (particularly infants’) attention to center screen if they have looked away. Saccade latency is defined as the time in milliseconds from trial onset to the initiation of an eye movement that resulted in a fixation (>100 ms) on the target item.

Procedure

Children, adolescents, and adults were specifically instructed to both look at and press to the target, using one of three buttons that correspond to the target identity and location using the first (←), second (↓), and third (→) finger of their right hand. Infants only saccade to items as they appear on the screen. As in SRT tasks, the location of the target and the corresponding response finger were always congruent, but stimulus-response correspondence was counterbalanced across subjects. No feedback was given. All speaking subjects were asked to describe what the task was about afterward. None showed awareness of the intricate task structure.

Data Preparation

We removed outliers, defined as grand mean ± twice the standard deviation, on a subject-by-subject basis. Saccade latencies and manual responses were then binned into four blocks for each condition. If a subject had no saccade latency data for a particular condition and trial block, that block value was replaced using a linear trend analysis with the remaining block averages as trend input. Any data loss reflects minor changes in head movement or pupil loss expected over the course of 104 trials, rather than lack of interest or inattention. On average, infants provided 87% of the binned data, children 98%, adolescents 98%, and adults 99%. Saccadic anticipations, defined as saccades to the target item location prior to target onset (less than 200 ms after trial initiation) were included in the latency data and only removed when they were outliers relative to the subjects’ average task performance. We reasoned that anticipations on high probability cue-target relation (75%) and high item occurrence (50%) trials, for example, would only serve to reduce average latencies per block, providing an important contrast to performance on the relatively low probability relations (25%) and low frequency item occurrence (12%) conditions. These patterns would be consistent with our learning measures.

EXPERIMENT 1

Participants

A total of 90 subject contributed data to this experiment. We tested 30 children (6–10 years, $M =$ 9.03 years, $SD = 1.59$ years, 16 females), 30 adolescents (12–16 years, $M = 13.27$, SD = 1.60 years, 18 females), and 30 adults (20–30 years, $M = 24.6$ years, $SD = 2.37$ years, 19 females). Families were recruited via advertisements in the local community and/or a letter and a follow-up phone call. Families were compensated for travel expenses. Parents gave informed consent and children provided assent in accordance with the Institutional Review Board (IRB) before the test session began. The sample racial distribution was the following: 40% Caucasian, 24% Black, 10% Hispanic, 12% Asian, 10% of mixed race, and 4% unreported. Prior to enrollment, we screened participants (self or parent report) for personal history of diagnosed psychiatric disorders (Tourette's, Obsessive Compulsive Disorder, Schizophrenia, Panic and Anxiety Disorders, Major Depression), uncorrected visual and auditory impairments, and preterm birth. None of these is represented in this sample. All subjects performed the Vocabulary and Matrix Reasoning subtests from the Wechsler Abbreviated Scale of Intelligence (WASI) for estimated IQ. All IQ scores were in the normal range and hence no exclusions were necessary. There were no significant group differences in IQ (Mean for children = 112, adolescents = 104, and adults = 115, p = n.s.).

Results

All reaction time and saccade latency data were log base-10 transformed to correct for any violations of the normality assumption. The Shapiro–Wilk test for normality verified that reaction time and saccade latency data normalized with this transform. Homogeneity of variance violations were Greenhouse–Geisser corrected. We corrected for multiple comparisons using the Bonferroni approach. Only significant results are reported.

Reaction Time

We statistically considered learning conditions (Tab. 1) and age groups in a 3 (Learning Conditions: High Probability Relations × Conflict-Low Probability Relations/ High Frequency Items × Low Frequency Items) × 3 (Age Group: Children × Adolescents × Adults) × 4 (Block) ANOVA on reaction times to correct responses. The analysis revealed a main effect of Condition, $F(1.7,\ 145.2) = 42.54$, $p = .000$. Paired t tests on planned comparisons showed slower responses to the low (12.5%) relative to the high frequency (50%) item occurrences and cue-target spatiotemporal relations (25% vs. 75%). Specifically, participants were slower in the Conflict (Low Probability Relations) relative to the High Probability Relations condition, $t(89) = 6.38$, $p = .000$, and faster in the Conflict condition when compared to the Low Frequency Items condition, $t(89) = 3.89$, $p = .000$. These data indicate that both statistics are being learned in the Conflict condition and that behavior is modulated by both parameters (see Fig. 1, top panel).

The ANOVA also revealed main effects of Block, $F(2.4,\ 211.9) = 30.99$ $p = .000$, and Age Group, $F(2,87) = 29.94$, $p = .000$. Children are generally slower than are adolescents, $t(50.7) = 5.78$, $p = .000$, and adults $t(58) = 6.82$, $p = .000$, Bonferroni-corrected alpha level set to $p = .017$ (.05/3). We also found a Block × Age Group interaction, $F(4.9,\ 211.9) = 4.76$, $p = .000$. We conducted a series of paired-samples t tests to examine this interaction (all Bonferroni alpha levels set to $p = .002$, .05/18). In general, reaction times become faster after the first task block. Relative to the first block, children are faster to both block 2, $t(29) = 7.13$, $p = .000$, and block 4, $t(29) = 3.73$, $p = .001$. Adolescents only show this effect reliably from block 1 to block 2, $t(29) = 5.64$, $p = .000$. Relative to block 1, adults are faster to block

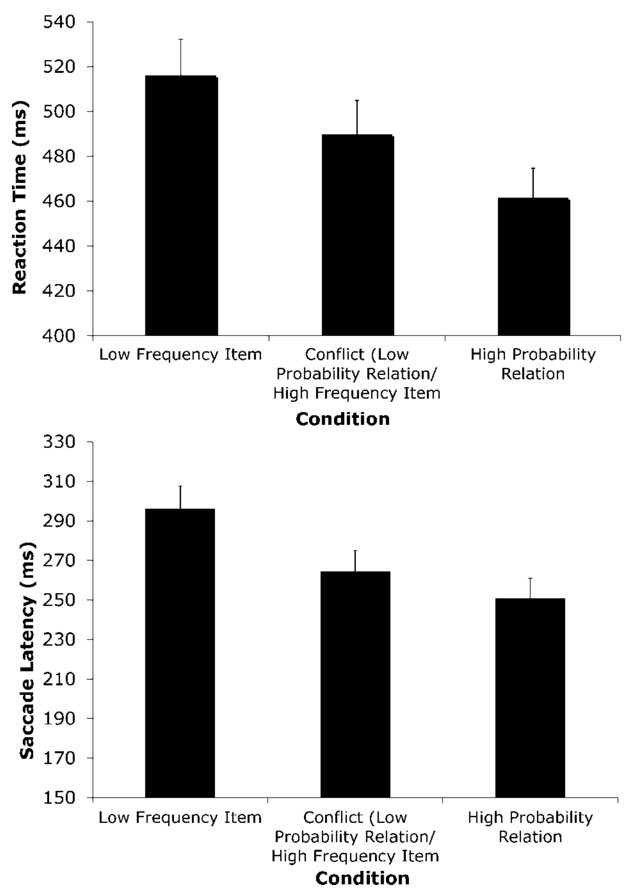

FIGURE 1 Illustrates performance on both reaction time and saccade latency indices of learning in Experiment 1.

2, $t(29) = 6.81$, $p = .000$, block 3, $t(29) = 6.24$, $p = .000$, and block 4, $t(29) = 6.82$, $p = .000$. Notably, these effects did not interact with condition and likely reflect increasing familiarity with the testing situation.

Finally, the omnibus ANOVA identified a Condition by Block interaction, $F(4.9, 421.6) = 4.81$, $p = .000$. We followed up on this predicted interaction using simple effects tests comparing our learning contrasts of interest. A cue-target spatiotemporal relations Condition (High Probability Relations 75% × Conflict—Low Probability Relations 25%) by Block (4) ANOVA yielded a reliable main effect of Condition, $F(1,89) = 39.46$, $p = .000$, with reaction times overall slower for the Low Probability Relations (Conflict) condition, but no reliable Condition by Block interaction. Low probability cue-target pairings are reliably slower in each block (see Fig. 2, all ps < .0125 Bonferroni-corrected alpha level). We next considered item frequency learning, controlling for relations, in a Condition (Low Item Frequency 25% × Conflict—High Item Frequency 50%) also revealed a main effect of Condition, $F(1,89) = 15.04$, $p = .000$ and a Condition × Block interaction, $F(2.7, 240.7) = 3.69$, $p < .05$. Participants are slower to the low relative to the high frequency item occurrences. This is reliable in blocks 2, 3, and 4 (see Fig. 2, all ps < .0125 Bonferroni-corrected alpha level). All subjects, with no age related differences in performance, were able to flexibly learn the task structure (see Fig. 2).

Saccade Latency

We repeated this analysis using the saccade latency data for comparison with infant patterns. Two children and one adult did not provide SL data. A 3 (Learning Conditions: High Probability Relations × Conflict-Low Probability Relations/High Frequency Items × Low Frequency Items) × 3 (Age Group: children × adolescents × adults) ANOVA revealed only a main effect of Condition, $F(1.8, 136) = 12.57$, $p = .000$. We examined this main effect with paired-samples t-tests on planned contrasts. As in the reaction time data, response to the Conflict—Low Probability Relations (25%) are slower than the High Probability Relations (75%), $t(85) = 2.53$, $p < .05$, and faster than the Low Frequency Item occurrences (12.5%), $t(85) = 3.26$, $p < .005$ (see Fig. 1, bottom panel). This suggests that the saccade latency data and manual response data approximate each other well and that implicit learning is not altered by input and response effectors. The analysis also revealed a block by age group interaction, $F(5.6, 215.2) = 2.3$, $p < .05$. However, follow-up tests yielded no reliable interpretable findings with respect to this interaction.

Accuracy

Accuracy values were excellent even for the youngest age group, and therefore not normally distributed with or without transformation. We therefore used the nonparametric Friedman test for related samples to examine error patterns. Only children showed reliable differences in errors pertaining to the learning conditions (Fig. 3). Specifically, the Friedman test yielded reliable differences for item frequency learning for the first ($p < .01$), second ($p < .05$), and third ($p < .05$) blocks for children only. With the exception of the first block, children make more errors to the Low Frequency Item condition than to the Conflict-High Frequency

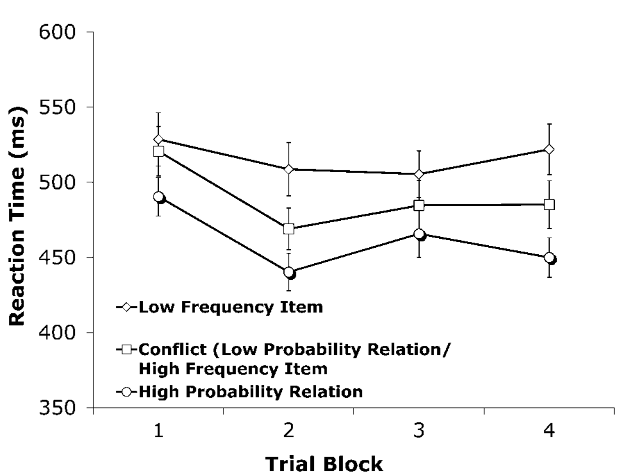

FIGURE 2 Illustrates reaction time performance on Experiment 1 as a function of task trial block.

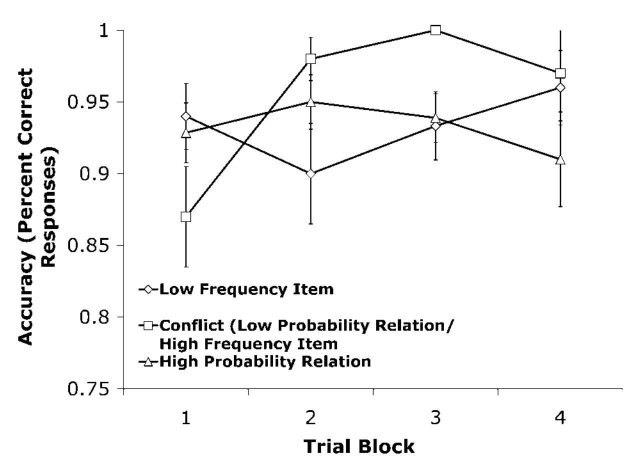

FIGURE 3 Depicts accuracy performance for children only in Experiment 1.

Item condition. Figure 3 shows that, unlike the reaction time and saccade latency data, the Conflict condition largely tracked item frequencies but not relations in the accuracy data. Analyses showed that children were actually making more errors to the High Probability Relations than to the Conflict-Low Probability Relations in the second ($p < .05$), third ($p < .01$), and fourth ($p = .001$) blocks. That is, the Conflict condition did not *also* track learning of item relations. This suggests that it is more difficult to adjust behavior when confronted with salient infrequent items than when confronted with unpredicted information in a particular context.

Discussion

Data from Experiment 1 provide evidence that participants can learn two parameters acting on the same item and adjust behavioral response in a manner that is relevant to the context. We found no differences in implicit learning as a function of age group in this age range, as revealed by reaction times or saccade latencies. All groups learned both statistics flexibly, as evidenced by the titration of response latencies in the conflict condition (Figs. 1 and 2).

The Conflict condition had a high error rate during the first task block. It is possible that this reflects the increased processing demands on behavioral flexibility inherent in this condition. Furthermore, children make relatively more errors to the low frequency items than to the high frequency items after the first task block, presumably having formed a strong motor representation of the high frequency item location that is difficult to override when confronted with low frequency item location. While response time data to the conflict condition indicate flexibility in response that is consistent with the task structure, accuracy data indicate that errors are driven largely by frequency of item occurrence violations after the first task block. This finding replicates Thomas and Nelson (2001), showing developmental invariance in learning on a SRT but poorer behavioral control and adjustment in children. Our finding extends this work by showing that flexible adjustment in behavior is more taxing when the single item is particularly salient than when a spatiotemporal cue-target relation is highly probable. This is consistent with the contention that single item memory is inflexible (Cohen et al., 1997) and with evidence of a protracted developmental course for the associated frontostriatal network as shown on go-no-go tasks (Durston, Thomas, Worden, Yang, & Casey, 2002).

These data raise two important possibilities. The first is that cognitive control during the learning process is itself not a unitary construct and is dependent on the specific information input. Cognitive control supporting efficient adjustments in behavior when learned information is violated shows variations in developmental performance as a function of its interactions with specific learning systems. Second, these data provide evidence for the developmental invariance model in learning from environmental regularities in this age-range. However, a great deal of developmental change occurs in the first six postnatal years. Experiment 2 considers performance on this task in infants.

An infant analogue to this task, in the sense that subjects incidentally learn from environmental regularities, may be statistical learning tasks. Saffran, Aslin, and Newport (1996) initially described statistical learning in a habituation paradigm where infants heard a string of nonsense syllables. Like the SRT task, three-syllable strings occur together sequentially and 100% faithfully. Head turn rates to novel triplets relative to the repeated triplet sequences indicated learning from environmental regularity. Although initially applied in the auditory modality, studies have since validated this form of learning in infants using tones and in the visual modality (e.g., Fiser & Aslin, 2001; Kirkham, Slemmer, & Johnson, 2002; Saffran, Johnson, Aslin, & Newport, 1999) as early as 2 months (Kirkham et al., 2002). However, the implicit learning SRT and the task used in this work may not share underlying mechanisms with statistical learning paradigms. Statistical learning presupposed learning of ordinal information, that is, conditional probabilities. However implicit learning focuses on the formation of memory chunks (Perruchet & Pacton, 2006). Marcovitch and Lewkowicz (2009) found that probability of pair co-occurrence influences sequence learning patterns independently of conditional probabilities in a group of infants. Lewkowicz and Berent (2009) found that infants do not track ordinal information when learning sequential structures in the visual domain. It is our view that more work needs to be done to shed light on similarities and differences between statistical learning work in the visual domain in infancy and implicit learning from environmental regularities.

Regardless, while our research question is different than that used in statistical learning work, we use the data provided by these studies (Fiser & Aslin, 2003; Kirkham, Slemmer, Richardson, & Johnson, 2007) to place our work in context. Data from the visual expectation paradigm (Haith, 1993) showed that infants can learn simple co-occurrence pairs. Fiser and Aslin (2003) used multi-element scenes and showed that by 9–11 months, infants were sensitive to spatial relations between element pair co-occurrences. Kirkham et al. (2007) considered sensitivity to spatiotemporal correlations of moving elements across the first postnatal year and found that 11-month olds were sensitive to spatiotemporal regularity when color/shape cues where held constant (same color circle appearing in location one followed by location 2). Eight-month olds required color and shape cues in addition to location statistics. These data indicate that some shift in learning of spatiotemporal information is occurring between 8 and 11 months. In light of these findings, we bin infants into 7–8 and 9–10-month groups to consider developmental changes in learning from regularities when conflicting information acts on items and relations between items. Our prediction is that both groups of infants will show learning patterns like those demonstrated in Experiment 1.

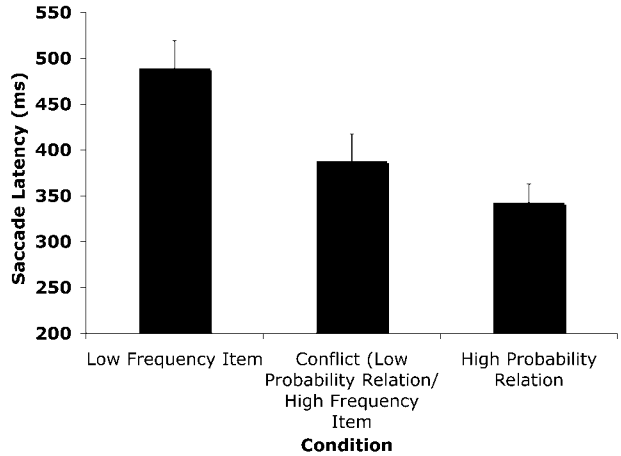

FIGURE 4 Illustrates saccade latency performance in infants in Experiment 2.

EXPERIMENT 2

Participants

A total of 22 infants participated in this experiment (14 females). We divided our sample into eleven 7- to 8-month olds ($M = 241$ days, $SD = 24$ days) and eleven 9- to 10-month olds ($M = 284$ days, $SD = 11$ days). One subject was excluded for providing too little data during the task. Infants were full term with no known developmental disabilities. Families were recruited via advertisements and/or a letter and a follow-up phone call. Parents gave informed consent in accordance with the Institutional Review Board (IRB) before the test session began. Families were compensated for travel expenses and infants received a certificate of completion as a thank-you gift. Infants were 60% Caucasian, 21% Hispanic, 7% Asian, and 12% of mixed racial background. Prior to enrollment, we screened participants (parent report) for first-degree relative history of diagnosed psychiatric disorders (Tourette's, Obsessive Compulsive Disorder, Schizophrenia, Panic and Anxiety Disorders, Major Depression), uncorrected visual and auditory impairments, and preterm birth. To our knowledge, none of these is represented in this sample.

Results and Discussion

Saccade Latencies. Infants were tested with the same task used in Experiment 1. Data were log base-10 transformed prior to analysis. We conducted a 3 (Learning Conditions: High Probability Relations × Conflict-Low Probability Relations/High Frequency Items × Low Frequency Items) × 4(Block) × 2 (Age Group) ANOVA. The analysis yielded only a main effect of Condition, $F(2, 38) = 9.81$, $p = .000$. Saccade latencies were slower to Low relative to High Frequency (Conflict) Item occurrences, $t(21) = 3.05$, $p < .01$, and marginally to Low (Conflict) relative to High Probability cue-target Relations, $t(21) = 1.85$, $p = .07$. Overall, infants learned both parameters early and maintained both over the course of the task, as indicated by latencies to infrequent relative to frequent item occurrences and cue-target relations (Fig. 4). The novel results provided by this experiment are that implicit learning in infancy is flexible enough such that two statistics can act in conflict on the same item, and that responses are titrated in accord with the input structure.

We were concerned that data loss in infants was disproportionately distributed across conditions with fewer trials; the treatment for this may have masked an otherwise reliable condition × block interaction. Infants overall contributed more binned data in the High Probability Relations condition (98%) than in either the Conflict (80%) or the Low Frequency Items conditions (88%). This differential between the High Probability Relation condition and the Conflict, $t(21) = 5.02$, $p = .000$, and Low Frequency Items conditions, $t(21) = 3.13$, $p = .005$ (Bonferroni corrected alpha set to $p = .004$) were significant only for the final task block. There were no differences in this distribution as a function of age group. Infants may have begun to lose interest in the task or become fatigued. Therefore, we re-conducted our analyses excluding the final task block and again found only a main effect of condition as described above, $F(2, 38) = 151.05$, $p = .000$.

GENERAL DISCUSSION

We tested children, adolescents, and adults (Experiment 1) and 7- to 11-month-old infants (Experiment 2) on the same paradigm designed to test implicit learning from environmental regularity. The global issue addressed in this work is whether implicit learning from environmental regularities is development invariant. We designed a task structure where subjects can learn based on simple item frequencies and/or higher order cue-target spatiotemporal relation pairings. We set these statistics in conflict in one condition, asking whether flexibility in learning from multiple parameters will act to constrain learning and alter the course of variance or invariance in development. Our task structure is such that items and pairs are high and low probability (rather than 100% faithful) to better understand how this interaction of control and learning systems may change over development.

We provide several novel additions to the implicit learning literature. Our data provide evidence that participants can learn two parameters acting on the same item (Conflict condition) as evidenced by response latencies to novel relative to familiar elements. We also provide support that there is developmental invariance in implicit learning from environmental regularity, independent of structural complexity and statistical conflict, and even when learning and maintaining more than once source of learned information. Reaction times tracked saccade latencies in Experiment 1. This is consistent with previous work (Kartekin et al., 2006), and ensures that our findings were not motor effector specific (De Guise & Lassond, 2001), allowing for a link between learning curves in Experiment 1 and infant saccade latencies in Experiment 2. A limitation of this work is that the sample size in Experiment 2 may have been too small to detect differences between the two infant age-ranges and we did not test a group of very young infants on this task. However, we find it very exciting that this group can learn such a task structure and show the cognitive flexibility patterns seen in Experiment 1.

Accuracy data showed that it is more difficult to control behavior, for children, when confronted with low relative to high frequency single items above and beyond cue-target spatiotemporal relations between items. Learning of single item information is inflexible, and the overriding of this information with novel inputs is taxing. Importantly, this ability to override learned responses in favor of a novel alternative, similar to reversal learning, is a key component in any developmental process. Inputs to the brain change frequently, both as a function of changing environments and as a function of the acquisition of novel skills that allow for different information uptake. Flexible behavioral adjustments allow the system to remain efficient and goal oriented. Therefore, although we found general developmental invariance in initial learning, future work will determine whether a different developmental pattern would emerge with reversal learning of single items.

The theoretical benefit of developmental invariance in learning from environmental regularities is clear. The human newborn has a limited set of tools with which to interact with the external environment. Yet, by the end of the first postnatal year, they have an immense amount of information about the world and are skilled both cognitively and socially. This has led many to postulate innate knowledge and/or specified modules for cognition. The alternative is that the immature brain is equipped with available learning and memory systems for gathering complex information for subsequent processing and storage. The compositional nature of relational memory coupled with the inflexibility of item specific learning may both provide important benefits for information gathering. Development then proceeds hierarchically and continuously, with acquisition of novel environmental structure both supported and constrained by what was previously learned.

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