Neurophysiological Correlates of Visual Statistical Learning in Adults and Children

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Abstract

Implicit statistical learning refers to the acquisition of statistical patterns occurring under incidental learning conditions. Although statistical learning is central to the development of many cognitive domains, such as language, its developmental trajectory is largely unspecified. Furthermore, few studies have attempted to examine the underlying neural mechanisms supporting statistical learning, in adults or in children. In this study, we used a novel visual statistical learning paradigm that allowed us to investigate the neurophysiological correlates of learning in adults, older children (aged 9-12), and younger children (aged 6-9). The results depict a nuanced picture of the development of statistical learning, involving the use of two distinct neurocognitive processing mechanisms associated with the N2 and P300 components. In addition, the results suggest that the children's brains acquired the statistical structure quicker than the adults, with learning-related ERP components emerging after comparably less exposure to the patterns.

Keywords: statistical learning, event-related potentials (ERP), cognitive development

Introduction

Implicit learning refers to the automatic, unconscious, and effortless acquisition of information that generally results in knowledge that is difficult to express verbally (Cleeremans, Destrebecqz, & Boyer, 1998; Eimer, Goschke, Schlaghecken, & Sturmer, 1996). One type of implicit learning is statistical learning, which refers to the acquisition of statistical patterns in the environment (Perruchet & Pacton, 2006). Implicit and statistical learning are believed to be important contributors to aspects of cognitive development, such as language acquisition (Conway, Bauernschmidt, Huang, & Pisoni, 2009). However, few still have probed the neural mechanisms mediating statistical learning in adults let alone children, making it difficult to specify the neurocognitive development of these learning processes.

Although Reber (1993) suggested that implicit learning is developmentally invariant, other researchers have provided evidence of developmental differences in implicit learning. In an fMRI study, Thomas, Hunt Vizueta, Sommer, Durston, Yang, and Worden (2004) found behavioral and functional neuroimaging differences in implicit learning between children 7 to 11 years of age and adults (also, see McNealy, Mazziota, & Dapretto, 2010). Furthermore, a pattern of development in implicit learning abilities has been detected between six-year-old and ten-year old children (Mecklenbräuker, Hupbach, & Wippich, 2003), and age-related implicit learning differences have been found between seven-year-old children and adults (Barry, 2007).

In most cases, where developmental differences in implicit learning is found, adults out-perform children. It perhaps is not surprising to see a developmental progression in statistical learning, with more basic abilities acquired first, followed by more involved processing components (Saffran, 2003). On the other hand, an alternative is that young children might actually possess better or more efficient learning mechanisms than adults. Some proposals take the somewhat paradoxical stance that cognitive limitations and/or reduced input may confer a computational advantage for learning (Conway, Ellefson, & Christiansen, 2003; Elman, 1993; Newport, 1990), which may explain the presence of sensitive periods in language development.

To explore these issues, the current study aims to investigate the neural mechanisms of visual statistical learning in both adults and children using the event related potential (ERP) technique. Some previous studies have used ERPs to investigate implicit learning in adults, with particular components associated with the acquisition of rule-based or statistical sequential patterns. One type of response, the N2, is observed as a negative-going deflection in voltage potential, appearing approximately 200 ms after the presentation of a stimulus. Another, the P300, is a positive deflection that appears about 300 ms after stimulus onset (Eimer, Goschke, Schlaghecken, & Stuermer, 1996; Ferdinand, Mecklinger, & Kray, 2008). These ERP components often appear together in learning studies (Schlaghecken, Stuermer, & Eimer, 2000), and it has been suggested that both components reflect stimulus-evaluation processes (Rüsseler & Roesler, 2000). Ferdinand et al. (2008) argue that the N2 indexes the detection of deviant stimuli, while the P300 reflects the evaluation of incoming information and the updating of contextual representations. It may also be possible to interpret these two components in terms of the degree to which automatic vs. controlled processing are involved, with the earlier N2 reflecting more automatic or implicit learning mechanisms.

For the present study, we developed a novel learning paradigm – based on the classic oddball task – that is conducive to the measurement of ERPs in both adults and children. The task involved viewing a stream of visual stimuli that contained covert statistical patterns governing the probability of a target stimulus occurring. ERPs were compared across three groups of participants (adults, older children, and younger children) for three different types of stimuli that reflected differing transitional probabilities (high-probability, low probability, and zero probability). Finally, we investigated ERP responses early in the task (first two blocks) versus later in the task (last two blocks, out of five blocks total) to ascertain how much exposure to the stimulus patterns is required before ERP evidence of learning occurs.

Method

Participants

Thirteen adults between 18 and 23 years of age (mean: 20.69; 9 female) participated. Also, two groups of children were recruited: older children (n = 9, mean: 10.55; range 9-12 years; 4 female), and younger children (n = 9, mean age = 7.44; range 6-9; 5 female). Adult participants were recruited from the undergraduate population of Saint Louis University or lived in the surrounding area. Child participants were recruited from the St. Louis metropolitan area. All participants were free from cognitive, neurological, and psychological deficits.

Experimental Paradigm

The visual statistical learning task involved participants viewing a serial stream of colored circles appearing in the center of the computer screen, one at a time. Participants were told to press a keypad whenever a target color (e.g., green) appeared on the screen. What participants were not explicitly told was that the target color was predictable to varying degrees depending on the color immediately preceding it. Each trial began with the presentation of one to five filler circles. After the filler circles, one of the three predictor circles would appear, determined randomly. Each predictor circle had its own unique color (determined randomly for each participant). When the high predictor color appeared, the target and filler circle followed 90% and 10% of the time, respectively. When the low predictor color appeared, it was followed by the target and filler circle 20% and 80%, respectively. When the zero predictor color appeared, it was never followed by the target, and was always followed by a filler. The possible trial sequences are illustrated in Figure 1.

Each circle was presented on the screen for 500 ms on a black background, followed by a black screen for 500 ms. For each of the three conditions of predictive probability, there were 50 trials (for a total of 150 trials), which were divided into five blocks of 30 trials each. Within each block, the trials were presented randomly.

Recording Technique

EEG data reflecting brain activity associated with the experiment was collected using a 128-channel high-density sensor net (Electrical Geodesics, Eugene OR). Standard sensor net application techniques were followed. Impedances were kept below 50 kilo-ohms, and the data was digitized by NetStation acquisition software (Electrical Geodesics, Inc.).

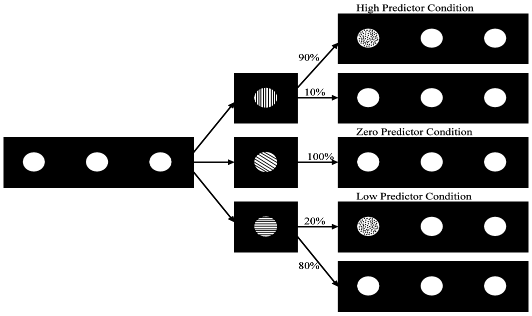

Figure 1: Sequence of colored circles for each of the three stimulus types (high-, low-, and zero-probability predictor conditions).

Following data acquisition, the continuous raw EEG recording was filtered through a 0.1 Hz high pass filter and a 30 Hz low pass filter. ERP recordings were time-locked to the onset of each predictor circle – not the target – using a 100 ms baseline, and continued for 900 ms after onset (for a total segment length of 1000 ms). This resulted in 50 individual trials for each of the three predictor conditions (high-, low-, and zero-probability). An artifact detection operation removed trials containing activity associated with eye blinks and other movements. Data from channels with poor signals were replaced with data extrapolated from surrounding channels in a bad channel replacement operation.

Based on previous ERP research, we expected that the N2 and/or P300 components would be present if participants had learned the statistical association between the high-probability predictor and the target. As these two components appear in the centro-parietal region of the scalp, this is where we focused, using a montage of 6 sensors corresponding to the 10-20 Pz electrode.

Results

Participants were told to press a button whenever the target color stimulus was presented on screen, which was predicted at different levels of probability by a predictor color. Thus, if learning has occurred, behavioral responses to the target should be facilitated when it is preceded by the high predictor color.

Although the primary goal of this study was to investigate the ERP correlates of learning, we also analyzed behavioral indices of learning by measuring reaction times (RTs) to the targets. A series of 2x2 repeated measures ANOVAs were conducted for each of the three participant groups separately, with the factors of block (first two blocks vs. last two blocks) and predictor (high vs. low predictor conditions). Note that because the target never is preceded by the zero predictor color, the zero predictor condition cannot be included. For the adult participants, RTs to the target decreased from the beginning to the end of the experiment, but only when it was preceded by the high predictor color (*F*(2, 38) = 3.70, *p*<.05). That is, by the end of the experiment, adult participants had learned that the high predictor was a reliable predictor of the target's appearance, as demonstrated by faster RTs to the target. However, neither group of children showed changes in RT for the high or low predictors, suggesting that they did not learn the statistical contingencies. On the other hand, another possible interpretation is that the children actually learned the statistical contingencies early in the experiment, and thus there was no change in RTs because of that.

A more complete picture should emerge by looking directly at the neurophysiological data, which may be a more sensitive measure of learning.

ERP Effects for Adults

Figure 2 shows the grand averaged ERP waveforms for the adult participants for each of the three predictor conditions. Visual inspection suggests that in the last two blocks, there is no N2 component. On the other hand, there is a very prominent late positivity – similar in appearance to a P300 component – that is associated with the high predictor condition specifically.

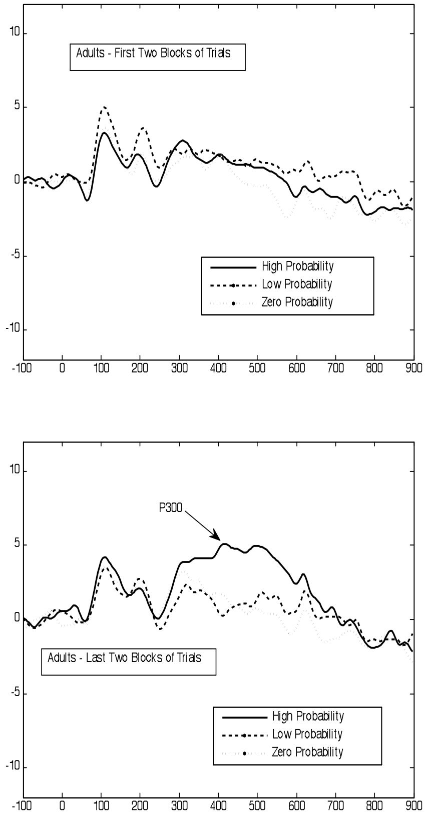

Figure 2: ERP waveforms in the Pz region for the adult group.

In order to verify the visual inspection, two 3x2 repeated measures ANOVAs were conducted using the mean amplitude waveforms as the dependent variable, and the factors of blocks (first two blocks vs. last two blocks) and predictor type (high, low and zero predictor conditions) for each of two latency periods of interest. The first period sought to examine potential differences related to the N2 component in the time window of 180 to 240 ms. The second time window was selected to examine the P300 component, using the window of 300 to 600 ms. The ANOVA and pairwise comparisons reported here and throughout the remainder of the paper were calculated using mean voltage deflections recorded at six electrodes centered on the location of the Pz sensor in a standard 10-20 montage. Reported *p* values are those reflecting the Greenhouse-Geisser correction for nonsphericity of variance.

In the time window 180 to 240ms post-stimulus, the 3x2 ANOVA found significant main effects for both predictor (*F*(2, 293) = 10.69, *p* < .001) and block (*F*(1, 35) = 5.96, *p* = .015), as well as for the interaction of predictor x block (*F*(2, 412) = 22.76, *p* < .001). For the present purposes, what is of most interest is whether an N200 manifested itself by the end of the experiment in the last two blocks, when learning would be expected to have occurred. Notably, pairwise comparisons indicated that there were no significant differences between the three predictors in the last two blocks (high versus low, *t*(209) = -1.05, *p* = .30; high versus zero, *t*(209) = -1.67, *p* = .10; and low versus zero, *t*(209) = 0.03, *p* = .98). This set of analyses highlights the lack of an N2 component in the adult participants for the last two blocks.

In the time window 300 to 600ms post-stimulus, a 3x2 ANOVA found significant main effects for both predictor (*F*(2, 1864) = 323.80, *p* < .001) and block (*F*(1, 974) = 563.70, *p* < .001), as well as for the interaction of predictor x block (*F*(2, 1768) = 340.61, *p* < .001). Importantly, pairwise comparisons indicated significant differences between the high versus low predictor conditions in the last two blocks (*t*(974) = 24.53, *p* < .001) and the high versus zero predictor conditions also in the last two blocks (*t*(974) = 29.42, *p* < .001). However, there was not a significant difference between the low versus zero predictor conditions in the last two blocks (*t*(974) = 1.17, *p* = .24). This set of analyses highlights the P300 component which presents itself in the adult data during the last two blocks.

In sum, the adult ERP data suggests that statistical learning – learning that the high predictor color was a reliable predictor of the target – was reflected by a P300-like component associated with the high predictor condition in the last two blocks. On the other hand, an N2 component was not observed.

ERP Effects for Older Children

Figure 3 shows the grand averaged ERP waveforms for the older children participants for each of the three predictor conditions. Visual inspection suggests some similarities as well as differences as compared to the adults. Specifically, the last two blocks look very similar to the adults in that there is not a prominent N2 component but there is a P300-like late positivity associated with the high predictor condition. On the other hand, in contrast to the adult data, there is evidence of a P300 occurring even early in the experiment in the first two blocks.

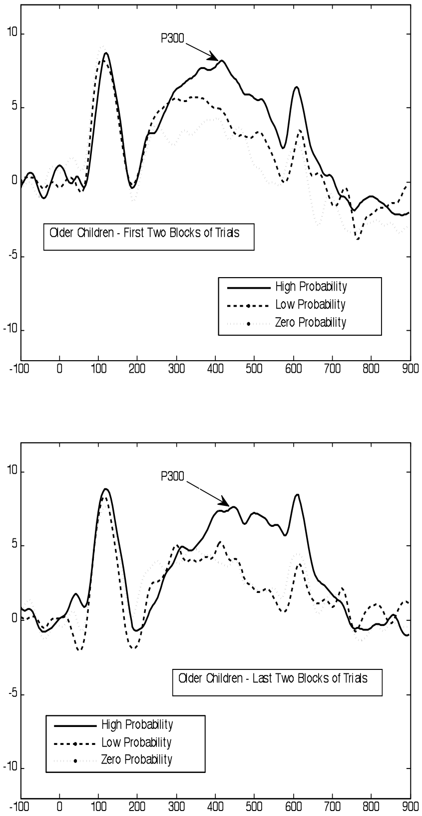

Figure 3: ERP waveforms in the Pz region for the older child group.

Two 3x2 repeated measures ANOVAs were conducted for each of the two latency periods as done with the adults. In the time window 180 to 240ms post-stimulus, the ANOVA found significant main effects for both predictor (*F*(2, 214) = 3.56, *p* = .04) and block (*F*(1, 134) = 16.84, *p* < .001), as well as for the interaction of predictor x block (*F*(2, 252) = 18.85, *p* < .001). Despite the main effect of predictor and the interaction, the expected N2 effect did not obtain in the last two blocks. Neither pairwise comparison involving the high versus low predictor were significant, in the first two blocks (*t*(134) = -0.22, *p* = .83) or the last two blocks (*t*(134) = 0.01, *p* = .99). This set of analyses highlights the lack of an N2 component in this group of participants.

In the time window 300 to 600ms post-stimulus, the 3x2 ANOVA found a significant main effect for predictor (*F*(2, 1161) = 185.71, *p* < .001), as well as for the interaction of predictor x block (*F*(2, 1339) = 8.47, *p* < .001). The main effect of block was not significant (*F*(1,674) = 1.66, *p* = .20). Relevant significant differences were found in the last two blocks between the high versus the low predictor conditions (*t*(674) = 9.92, *p* < .001) and the high versus the zero predictor conditions (*t*(674) = 11.07, *p* < .001). In addition, the pairwise comparison for the high predictor condition in the first two blocks versus the high predictor condition in the last two blocks was not significant (*t*(674) = -0.35, *p* = .72). These analyses demonstrate not only the appearance of the P300 component in this group by the end of the experiment, but also that this component appeared to be present even early on in the experiment, in the first two blocks.

Thus, despite the behavioral data suggesting that learning did not occur, the ERP data presents compelling neurophysiological evidence that just like the adults, a P300-like component was elicited by the end of the experiment for the high predictor condition, suggesting that learning did indeed occur. Strikingly, this group of older children also showed evidence of the P300 component occurring earlier in the experiment than did the adults.

ERP Effects for Younger Children

Figure 4 shows the grand averaged ERP waveforms for the younger children participants for each of the three predictor conditions. Visual inspection suggests some similarities as well as differences as compared to the adults and older children. Similar to both the adults and older children, there is a P300-like component in the last two blocks associated with the high predictor condition; this P300 component does not appear robust in the first two blocks. In contrast to the other two groups, there is also a prominent N2 component that occurs both in the beginning and ending blocks of the experiment.

To verify the visual inspection, two 3x2 repeated measures ANOVAs were conducted for each of the two latency periods as was done with the other two participant groups. In the time window 180 to 240ms post-stimulus, the ANOVA found significant main effects for both predictor (*F*(2, 221) = 24.27, *p* < .001) and block (*F*(1, 134) = 24.34, *p* < .001), as well as for the interaction of predictor x block (*F*(2, 213) = 14.91, *p* < .001). There were significant differences in the last two blocks between the high versus the low predictor (*t*(134) = -5.87, *p* < .001) and the high versus the zero predictor (*t*(134) = -5.61, *p* < .001) suggesting the occurrence of an N2. In the first two blocks, the high predictor also was significantly different than both the low (*t*(134) = -2.83, *p* = .005)) and zero predictors (*t*(134) = -6.98, *p* < .001)). This set of analyses demonstrates the presence of an N2 component for the high predictor condition in both the first two and the last two blocks.

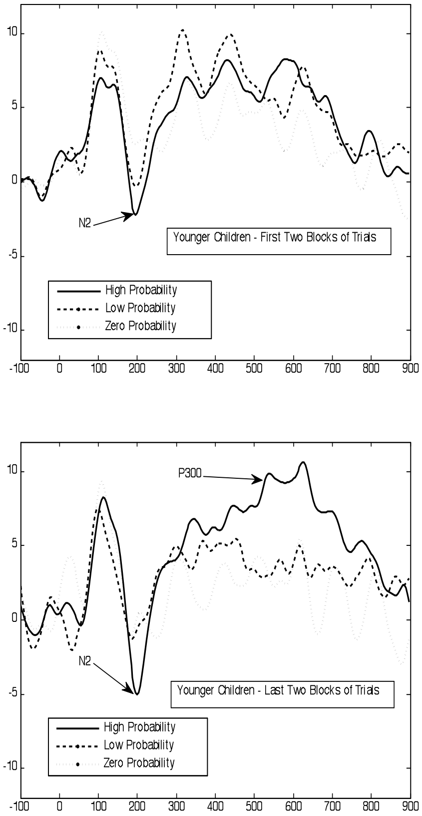

Figure 4: ERP waveforms in the Pz region for the younger child group.

In the time window 300 to 600ms post-stimulus, the 3x2 ANOVA found a significant main effect for the predictor (*F*(2, 1113) = 71.03, $p < .001$) and block (*F*(1, 674) = 26.96, $p < .001$), as well as for the interaction of predictor x block (*F*(2, 1246) = 88.17, $p < .001$). The high predictor was significantly different than both the low and zero predictors in the last two blocks, but was not different from the low predictor in the first two blocks (*t*(674) = -1.38, $p = .17$), suggesting that the P300-like component did not emerge until the end of the experiment.

In sum, like the adults, a P300-like component was found that did not fully emerge until the last two blocks of the experiment. On the other hand, unlike the adults and older children, the younger children also displayed an N2 response for the high predictor stimuli that was present even very early in the experiment.

Discussion

In contrast to previous findings suggesting developmental invariance or a steady developmental progression of implicit statistical learning abilities, these neurophysiological findings create a more nuanced picture. For the adult group, a statistically significant positivity was seen in the Pz region in response to the presentation of the high-probability predictor, in the time window 300 to 600 ms post onset, similar to a P300. This ERP was observed during the last two blocks of trials presented, but not during the first two blocks, suggesting that, during the course of the experiment, the participants implicitly learned the statistical patterns that governed the occurrence of the target. Importantly, this P300 effect for the high predictor stimuli was elicited even though the three predictor types were perfectly equated in terms of their overall frequency of occurrence. The P300 is an index of target detection and evaluation (Van Zuijen et al., 2006), and also has been elicited in other types of implicit sequence learning and statistical learning tasks (Baldwin & Kutas, 1997; Carrión & Bly, 2007; Rüsseler et al., 2003).

The group of older children (ages nine to 12) also displayed a learning-related P300 component but appeared to differ from the adult group in the rate at which it emerged. While the adults did not display any evidence of a P300 in the first two blocks of trials, the older children showed it even at this early stage in the experiment. This result suggests that children at this age are able to learn visual statistical sequential patterns given less exposure to stimuli (i.e., fewer trials) than adults.

The ERP responses of the group of younger children (ages six to nine) to the high-probability predictor showed both similarities and differences compared to those of the adults and the older children. Like both the adults and older children, the younger children displayed a learning-related P300 in the last two blocks. Unlike the older children, the younger children did not show evidence (in the form of a P300) that they had acquired this knowledge during the first two blocks of trials. On the other hand, there appears to be an N2 response to the high-probability predictor even in the first two blocks of trials. The amplitude of this early negativity is greater in the last two blocks, and clearly distinguishes the response to the high-probability predictor from the responses to the zero-probability and low-probability predictors.

This pattern of ERP responses suggests a complex developmental progression in visual statistical learning abilities. Children between the ages of roughly six to nine appear to rely on a distinct cognitive learning mechanism associated with the N2 component. Because the N2 is a relatively early component, its elicitation may signify a more automatic and implicit learning mechanism, which builds up knowledge efficiently and quickly. In turn, the P300, a relatively late latency component, emerges only following additional exposure to the statistical patterns, and may signify more consciously-mediated or controlled processing mechanisms. After sufficient exposure to the stimulus patterns, these younger children display both the N2 and P300 responses to the high-probability predictor, implying that both learning mechanisms contribute to young children's statistical learning.

Older children between the ages of about nine to 12 appear to rely more heavily on the more controlled processing mechanism reflected by the P300 than by the automatic learning mechanism reflected by the N2. For this group of older children, a P300 response first appears during the first two blocks of trials. This stands in contrast to the response of the younger children, who displayed an N2 response, but not a P300, in the early trials, and to the response of the adults, who did not show any evidence of learning during the first two blocks of trials. In other words, both groups of children differ from adults in that knowledge resulting from statistical learning appears to develop more quickly in both groups of children, though mediated by different learning mechanisms.

One similarity between the adults and the older children can be found in the latency of the P300 ERP response. For these groups, the waveform for the high-probability condition diverges from the waveforms for the low-probability and zero-probability conditions between approximately 300 and 600 ms following the onset of the predictor circle. For the group of younger children, the latency of the late positivity in the high-probability condition is shifted roughly 100 ms later, beginning at about 400 ms and ending around 700 ms. This, together with the earlier appearance of the P300 in the group of older children, suggests that the learning mechanism associated with the P300 response is not fully developed in children until the age of nine.

Conclusion

This study investigated the development of the neurocognitive mechanisms underlying visual statistical learning. Whereas adults and older children relied exclusively on a learning mechanism associated with the P300 component, younger children relied primarily on an N2-related component, perhaps reflecting that their learning is more automatic and intuitive in nature. Even more striking is that both groups of children displayed neurophysiological evidence for learning earlier – i.e., after fewer trials – than the adults. This last effect may indicate that the child's brain is 'primed' to learn, despite showing poor behavioral learning effects, and even may be related to sensitive periods in language acquisition. Future research must further explore the distinction between the two types of learning mechanisms observed here, and how the development of these abilities relate to language and other cognitive learning domains.

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