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Novel Insights into Statistical Learning

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Abstract

The brain has a powerful capacity for statistical learning–an ability to detect statistical regularities in the environment in order to make predictions and guide behaviour–often without conscious awareness. It has been claimed that statistical learning plays a key role in a range of everyday perceptual and cognitive processes including those associated with language. There is demonstration that both spoken and written forms of natural language contain a rich statistical structure and there is demonstration that artificial languages are easier to learn when they contain statistical regularities. And yet, to date, there is very little empirical data showing a direct link between a capacity for statistical learning and proficiency with natural language. Here we report on a study of visual statistical learning that provides two important insights in the quest for such empirical evidence: this capacity follows a developmental trajectory in typically developing children, and it is correlated with reading ability.

Keywords: statistical learning; visual statistical learning; reading.

Statistical Learning

The capacity for statistical learning (SL) can be assessed in a number of ways, for example, by presenting a continuous stream of evenly paced, individually presented items (be they objects, shapes, scenes, syllables, tones – represented here by letters) that contains embedded triplets such as …J–K–L–D–E–F–J–K–L–A–S–C… After brief exposure, participants are surprised with a forced-choice familiarity task and are able to identify embedded triplets (such as JKL) more reliably than foil triplets. This effect occurs even though (1) all individual items have been presented an equal number of times (2) there was no advance warning that there would be embedded patterns in the stream and (3) there was an absence of any kind of reinforcement. Participants often do not have any conscious sense of familiarity even when they exhibit significant levels of SL.

A seminal study demonstrated that 8-month-olds can detect statistical patterns embedded in pseudospeech after only 2 minutes of exposure (Saffran et al., 1996). There is suggestion that SL might begin in utero (e.g., DeCasper et al., 1994; DeCasper & Spence, 1986) and evidence that it can operate on non-linguistic stimuli such as musical tones (e.g., Creel et al., 2004). To date, the majority of investigations of SL have examined the processing of auditory stimuli (ASL) although the number of studies examining visual stimuli (VSL) is steadily growing. A foundational study of adults' ability to learn temporal relationships amongst visually presented shapes indicated significant SL after only 6 minutes of exposure (Fiser & Aslin, 2002). Recently, it was shown that infants less that a year old possess the capacity for VSL (Kirkham et al., 2002). There has been demonstration of the learning of position-dependent and position-independent statistical regularities using visually presented shapes (e.g., Fiser & Aslin, 2001) and the learning of real world scenes (Brady & Oliva, 2008).

The claim that SL plays a key role in the acquisition of language stands in contrast with the persuasive notion that language is too complex and the language learner's environment too impoverished for language acquisition to be subserved by a general learning mechanism. These views, combined with an assumption that cognitive functions are organized in a modular way, has led to the suggestion that language acquisition might be subserved by an innate mechanism (preprogrammed with information about linguistic universals). Patterson and Plaut (2009) cited Chomsksy: "…we take for granted that the organism does not learn to grow arms or to reach puberty…. When we turn to the mind and its products, the situation is not qualitatively different from what we find in the case of the body" (Chomsky, 1980, p. 2). The role of endowment versus learning during language acquisition has led to high-level and often feisty debate. Little attention has been given to a third possibility that incorporates both viewpoints – described as a kind of "innately guided learning" (Gould & Marler, 1987, p. 62; Yang, 2004).

A lack of empirical evidence is preventing further scientific advances in this area – "current conceptualizations of these problems are driven more by theory than by data." (Gomez & Gerken, 2000, p. 180) In fact, it is premature to claim that SL has a significant role to play in language acquisition. There has been very little investigation of a link between a capacity for SL and spoken language proficiency. In a retrospective study, Newman et al. (2006) found that speech segmentation ability in infants (often attributed to SL) was linked to later proficiency with natural language at age 2 and 4–6. To our knowledge, there has been no examination of whether the capacity for SL is associated with the acquisition of written language. This latter gap in the research is surprising given the fact that children must be guided into a prolonged (and often effortful) period of *learning* how to read (i.e., reading, unlike speech, generally does not appear spontaneously).

A first step in the quest for evidence directly linking SL and acquisition of natural language is to consider the nature of SL, in particular, whether it follows a developmental trajectory (as linguistic proficiency does).

Developmental Effects of Statistical Learning

There has been no purpose-designed study of the variability of SL in the 'normal' population and, more specifically, of a possible age-related trajectory of VSL. Kirkham et al. (2002) examined VSL in 2-, 5- and 8-month-olds. The study was ground breaking in its demonstration of VSL in young infants (akin to the seminal study of ASL conducted by Saffran et al., 1996). Results showed that infants learn the embedded transitional probabilities present in sequences of visually presented shapes after only a few minutes of exposure and without any reinforcement. There appeared to be no age-related effects.

It has been suggested that "Such findings of age invariance stand in sharp contrast to most other phenomena in developmental psychology, for which the most obvious and gross generalisation is that performance improves with age." (Saffran et al., 1997, p. 101) An early maturing and biologically pre-programmed capacity for statistical learning may have an important adaptive function. It is our view that age-related effects during VSL have not been thoroughly investigated. The Kirkham et al. (2002) study examined three groups of infants, all of them under one year of age. Perhaps it is the case that there are no significant developmental changes in VSL in the first year of life. Alternatively, developmental changes associated with VSL might be observed over larger increments of time (i.e., in increasing years of age rather than increasing months). It seems possible that the inclusion of a larger number of children from a more varied range of ages might increase sensitivity and be more likely to lead to the detection of developmental differences in SL.

A Possible Relationship Between Visual Statistical Learning and Reading Ability

SL has most often been discussed in relation to phoneme discrimination (e.g., Maye et al., 2002), identification of word boundaries (e.g., Finn & Kam, 2008), acquisition of syntactic structure (e.g., Rowland & Pine, 2000) and vocabulary growth (e.g., Yu, 2008) – generally in the context of spoken language. Reading involves the ability to successfully learn the significance of a variety of visual patterns (as well as other skills such as those pertaining to letter knowledge, phonological awareness, and vocabulary). For example, when children are learning to read they need to detect the co-occurrence of particular pairs of letters within words such as 't' + 'h', 'p' + 'h', 'c' + 'h' and 's' + 'h' which need to be mapped onto entirely different phonemes than either of their contributing singleton consonants. They also learn about legal and illegal letter combinations such as English words can end with double letters (e.g., 'nn' in 'inn') but don't usually begin with double letters. In fact, there is a substantial body of evidence to suggest that there is rich statistical structure in written language that can be used to guide children's literacy development (for some recent work in this area see Arciuli & Cupples, 2006; 2007; Arciuli & Monaghan, 2009; Deacon et al., 2008; Monaghan et al., 2008, Seva et al., 2009; Treiman & Kessler, 2006).

The Current Study

In the current study we focused on VSL. Brief, reliable, child-friendly VSL tests are not widely available. Most tests of SL are designed for either infants or adults and while some of these might be appropriate for use with primary aged children there did not appear to be any immediately obvious examples of such tests. Thus, a key aim of this study was the creation of a test of VSL suitable for children aged 5-12 years. We speculated that an important step in the quest for direct evidence of a link between SL and proficiency with natural language is to ascertain whether SL follows a developmental trajectory. We then sought to determine whether there is a link between a capacity for VSL and reading ability.

Experiment 1: Creating a Test of VSL and Determining Age-Related Effects

Method

Participants Fifty-seven children (mean age of 9:6; range 6:1-12:4) with no known learning, language, hearing or speech impairments took part. All were native monolingual speakers of Australian English. Participants are summarized by age in Table 1.

Table 1: Num. of Subjects Broken Down by Age in Years

Age (years)	6	7	8	9	10	11	12	Total
All	6	7	5	14	11	8	6	57
Retained	5	6	5	14	11	8	6	55

Apparatus and Materials Twelve cartoon-like figures were chosen as stimuli for the experiment. The 12 'aliens' were divided into four groups of three (four base triplets) referred to as ABC, DEF, GHI and JKL.

Design and Procedure Children were tested individually. In the *familiarization phase* participants saw a continuous stream of 312 individually presented aliens. Each alien was visible for 800msec with a 200msec gap separating each alien. Thus, the entire familiarization stream lasted 311.8sec. Although participants were told that the aliens were presented in a random order, the aliens always appeared as part of their base triplet (e.g. alien D always immediately preceded alien E which in turn always immediately preceded alien F). The order of the triplets, however, was randomized. Occasionally, one of the alien figures was repeated, and this provided a cover task – the ‘alien alert’ task, with participants required to press the space bar whenever they saw a repeated alien. In total, there were 24 repeated aliens with each of the 12 individual aliens repeated on two occasions. Immediately following the familiarization phase, the *test phase* commenced. For each trial in the test phase participants saw two triplets (presented one after the other), one which had been present in the familiarization phase (e.g. GHI) and one which had not been present (e.g. DHL). Within each test triplet, each alien was presented individually, and was visible for 800msec with a 200msec gap separating each alien. Presentation of aliens within a test triplet was therefore identical to how they were presented in the familiarization phase. A 1000msec gap separated the two triplets in each test trial. Participants were required to identify which of the two triplets had previously been present in the familiarization phase. Each participant completed 64 trials in the test phase with no time restriction placed on their responses. The mean time to complete the test phase was 10.2 minutes (S.D. 1.2 minutes).

Results

Data from the familiarization phase were inspected to determine the number of repeated aliens successfully identified by each subject. Subjects who failed to identify at least half of the repeated aliens were excluded on the grounds that they may not have been attending to the familiarization stream. As a result of this screening two participants were removed from further analysis (see Table 1). The average number of correct responses on the test trials for the remaining 55 participants was 61.3%. This was significantly above chance performance of 50%, $t(54) = 4.747$, $p < .0005$. A Pearson’s correlation was performed between the participants’ performance in the test phase and their age in years. This proved to be significant, $r = .317$, $p < .05$. As age increased, the amount of VSL demonstrated by the participant also increased.

Discussion

To date, much of the research on SL has examined the processing of stimuli presented in the auditory modality in either infants or adults. As far as we are aware, there has not yet been an investigation of VSL in primary aged children. We are aware of only one previous study that has examined the effects of age on VSL (Kirkham et al., 2002) – in infants. That study found that age did not affect statistical learning and so is not, at first glance, in line with the present study which found that age was significantly correlated with VSL performance in typically developing primary aged children. Kirkham et al.’s study is invaluable in advancing our understanding of VSL in infants; however, it might not have been sensitive enough to detect age-related changes in statistical learning as Kirkham et al. examined three groups exhibiting very small differences in age (all participants were under one year of age). In the current study we sought to provide empirical evidence that would speak directly to this question of age invariance by investigating children across a broader age range. Our results indicate that VSL is affected by age. It could be suggested that our effects might be accounted for by children’s ability to properly attend during the tasks. However, we have reasons to believe this is not the case. First, as described in our Results section, we excluded participants who did not perform accurately during familiarization; for example, one child aged 8 identified only 37.5% of the repeated aliens and registered 20 false positives. Second, we analyzed the retained group data to see whether performance deteriorated over time and found no significant differences in performance between the first and second half of the Test Phase.

Experiment 2: VSL and Reading Ability

To date, the link between statistical learning ability and language acquisition has most often been discussed in relation to phoneme discrimination, identification of word boundaries, acquisition of syntactic structure and vocabulary growth – in the context of spoken language skills. Reading and spelling processes involve the ability to successfully learn visual patterns (as well as other skills). We sought to determine if there is a direct link between VSL ability and literacy skills.

Method

Participants A separate group of forty-two children (mean age of 9:1; range 5:10-12:5) with no known learning, language, hearing or speech impairments took part. All were native monolingual speakers of Australian English.

Table 2: Num. of Subjects Broken Down by Age in Years

Age (years)	5	6	7	8	9	10	11	12	Total
All	1	8	7	6	4	6	6	4	42
Retained	0	6	6	6	4	6	6	4	38

Apparatus, Materials, Design and Procedure Children were tested individually. The VSL test was identical to Experiment 1 apart from one change. During familiarization individual aliens were only visible for 400msec with a 200msec gap separating each alien. It was thought that shortening the presentation time would strengthen our claim that triplet recognition in the test phase was due to statistical learning rather than being the result of some other, consciously controlled cognitive process. After the VSL test had been completed, participants were administered the reading aloud subtest of the WRAT-4 (Wilkinson & Robertson, 2006).

Results

Four subjects were excluded due to poor performance in the familiarization phase (see Table 2). Three subjects were excluded because they failed to identify at least half of the repeated aliens. In addition, one subject was found to have an excessive number of false positives; that is, indicating that they had detected a repeated alien when no repetition was present on 64% of their responses. This subject was excluded on the grounds that it was unlikely that they fully understood what was required of them throughout the experiment. The average number of correct responses for the remaining 38 participants was 56.3%. This was significantly above chance performance $t(37) = 3.544$, $p < .005$. There was a trend for VSL performance to increase as age in years increased but the Pearson's correlation between these two factors just failed to reach significance, $r = .297$, $p = 071$. Scores on the reading subtest of the WRAT-4 ranged from 24 correct to 56 correct (out of a total of 70). We conducted a correlational analysis between the performance on the WRAT-4 and performance on the VSL test, partialling out age in years. Results showed a significant correlation between the WRAT-4 and VSL, $r = .327$, $p < .05$. We conducted a second correlational analysis, this time partialling out grade rather than age. Once again there was a significant correlation between the WRAT-4 and VSL, $r = .364$, $p < .05$. Higher levels of VSL performance were associated with better reading performance.

Discussion

Replicating the results from Experiment 1, the children in Experiment 2 exhibited VSL performance that was significantly above chance levels. A key finding from Experiment 1, that of a significant correlation between age and VSL performance, just failed to reach significance in Experiment 2 ($p = .071$). However, the number of retained subjects for Experiment 2 was lower than for Experiment 1 (38 v 55). We feel that had the numbers been higher, this result might have been replicated.

It has been argued that the ability to detect statistical regularities in input or mental representations contributes in a fundamental way to natural language acquisition. This claim is hotly debated in the literature (e.g., see Gomez & Gerken, 2000; Newport & Aslin, 2004; Pena et al., 2002; Saffran et al., 2008; Seidenberg, 1994; 1997; Seidenberg et al., 2002; Yang, 2004). However, empirical research regarding direct links between the capacity for statistical learning and proficiency with natural language is lacking.

Here, we investigated a possible link between VSL and literacy in typically developing primary-aged children. We administered our novel test to assess VSL and also administered a well-accepted test of reading (WRAT-4). Results revealed that our VSL test elicited statistical learning in the form of a significant group effect. The average degree of learning we obtained in Experiment 2 (56.3%) was smaller than we saw in Experiment 1; however, speed of presentation was faster in Experiment 2 and the degree of learning was similar to that of other published studies of VSL (e.g., 59% for fast presentation speeds as reported by Turk-Browne et al., 2005). Correlational analyses revealed a significant relationship between VSL and reading ability. Children who learned more of the transitional probabilities embedded in the stimuli during the VSL test also demonstrated higher reading ability. This relationship was shown to be independent of age and also grade.

General Discussion

In Experiment 1 we demonstrated a relationship between visual statistical learning and age. This indicates that the capacity for VSL follows a developmental trajectory in typically developing children. This is an important finding because it establishes that VSL is not invariant and that it can be affected by a participant-related factor, in this case, age. While this result was not replicated in Experiment 2, the same trend was present, and we believe that this apparent discrepancy might be explained by the fact that there were fewer participants in Experiment 2. In our second Experiment, we found a correlation between VSL performance and reading ability. This is an exciting finding because, although it has often been suggested that SL may play a role in natural language acquisition, for the first time, a direct link can be made between statistical learning performance and an aspect of literacy skill, specifically, reading aloud.

Clearly, there are a number of factors at play during the highly complex cognitive task of reading. For instance, we know that phonological awareness (PA) is a key predictor (if not the best predictor) of reading ability (see, for example, Adams, 1990; Kirby, Parrila & Pfeiffer, 2003; Lundberg, 1991; Stanovich, 1991; Torgesen et al., 1999). PA is the ability to understand the sound structure of language and, with regard to reading in English, the ability to understand how this sound structure maps on to letters of the alphabet. While VSL might play a role in reading independently of PA, it seems to us that that the link between VSL and reading might operate via PA. Being able to detect co-occurring letter combination such as 'th', 'ph','ch' and 'sh' is one thing but there is also the requirement of mapping these co-occurrences onto phonology. It seems possible that PA could, in fact, reflect statistical learning for both auditory input (ASL) and visual input (VSL). PA might be related to the ability to combine ASL and VSL in a meaningful way. Future research is needed to explore this. A further possibility would be to develop a VSL-based test that could be used to screen for subjects who may be at risk of developing reading problems. Certainly, VSL can be tested in young children long before they start to read. In any case, we hypothesized that VSL does play a role in reading and the results reported here indicate this to be the case.

There are a number of other directions for future studies to pursue. For instance, it would be valuable to compare VSL performance across a greater range of ages (from pre-schoolers to older adults). In addition, as suggested by Turk-Browne et al. (2005), it would be interesting to attempt to determine the absolute upper and lower limits of performance concerning speed of presentation. Note also that a capacity for rapid information processing (e.g., rapid item identification and rapid serial processing of series of items) has been linked with increased reading ability (predictors of reading ability are reviewed by Bowey, 2007 and Wolf, 2008 amongst others). While statistical learning might be shown to be easier with longer stimulus presentation times, perhaps the capacity for VSL at faster speeds facilitates language learning (in combination with age-related increases in the capacity for SL).

In showing that VSL is a variable capacity and is linked to reading ability, our results help to explain individual variation in perceptual and cognitive activities thought to rely, at least in part, on VSL. We consider this to be one of the most interesting avenues for future research - the direct examination of the influence of VSL ability on a variety of everyday mental activities.

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