The Developmental Trajectory of Children's Statistical Learning Abilities

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Abstract

Infants, children and adults are capable of implicitly extracting regularities from their environment through statistical learning (SL). SL is present from early infancy and found across tasks and modalities, raising questions about the domain generality of SL. However, little is known about its' developmental trajectory: Is SL fully developed capacity in infancy, or does it improve with age, like other cognitive skills? While SL is well established in infants and adults, only few studies have looked at SL across development with conflicting results: some find age-related improvements while others do not. Importantly, despite its postulated role in language learning, no study has examined the developmental trajectory of auditory SL throughout childhood. Here, we conduct a large-scale study of children's auditory SL across a wide age-range (5-12y, N=115). Results show that auditory SL does not change much across development. We discuss implications for modality-based differences in SL and for its role in language acquisition.

Keywords: statistical learning; developmental differences

Introduction

One of the deepest questions in cognitive science is how children learn about the structure of their environment. A fruitful line of work on this question examines the ability to extract knowledge about the world via statistical learning. Statistical learning (SL) refers to the ability to implicitly detect recurring patterns in sensory input based on statistical properties, and use them to learn higher order structure, like that found in language (Romberg & Saffran, 2010; Thiessen & Erickson, 2015). The term "SL" was originally coined in a speech segmentation study showing 8-month-old infants can use transitional probabilities between syllables as a cue to word boundaries (Saffran, Aslin, & Newport, 1996).

In the past two decades, numerous studies have shown that SL is present from very early infancy (Bulf, Johnson, & Valenza, 2011, Kuhl, 2004), in a variety of modalities (auditory, visual and tactile, see Conway & Christiansen, 2005), and can facilitate learning across a range of linguistic domains (Saffran, 2003) – from phonemic inventory (Maye, Werker, & Gerken, 2002), through word order preferences (Gervain, Nespor, Mazuka, Horie, & Mehler, 2008), to syntax (Gomez & Gerken, 1999). This body of literature illustrates learners' ability to extract structure by attending to distributional regularities in their environment.

However, while SL has been studied extensively with infants and adults, much less work has looked at how these abilities develop from infancy to adulthood, even though such findings are crucial for understanding the role and nature of SL abilities. The paucity of research leaves an important question unanswered: What is the developmental trajectory of SL across childhood? Is SL an early-maturing capacity that is stable in an individual across development, or does it improve with age? On the one hand, SL is already present in very young infants and postulated to play a role in language acquisition, suggesting it is an early-maturing capacity. On the other hand, most other cognitive abilities do develop with age.

Only few studies have looked at how SL abilities change during development and they show a mixed pattern of results (see detailed review in the next section): while some argue SL is age-invariant (e.g., Saffran, Newport, Aslin, Tunick, & Barrueco, 1997), others report an improvement with age (e.g., Arciuli & Simpson, 2011). Because these studies examined SL in different modalities (auditory vs. visual), it could be that the effect of age differs across domains. Importantly, although SL is found in multiple modalities and with various sensory inputs (e.g., Conway & Christiansen, 2005), there is growing evidence for modality-based differences in adults' SL abilities (Frost, Armstrong, Siegelman & Christiansen, 2015; Krogh, Vlach & Johnson, 2012). If SL is a unitary capacity, we may expect it to develop similarly across modalities. In contrast, a modality-specific mechanism may show different developmental trajectories in different modalities. However, there is little data that can be brought to bear on these questions.

SL Across Development

In theory, there are several possible predictions on the developmental trajectory of SL. The first is that SL improves with age, just like many other cognitive abilities (e.g. working memory, see Gathercole, Pickering, Ambridge & Wearing, 2004). This prediction is also motivated by recent findings from the field of implicit learning. SL is often seen as a type of implicit learning, occurring without explicit intent and/or overt awareness (Perruchet & Pacton, 2006). Traditionally, implicit learning mechanisms were considered to be age-invariant: they were seen as early-maturing and automatic capacities that do not improve with age (Reber, 1993). Yet this view has been challenged in recent years (Lukács & Kemény, 2014). While some studies support age-invariance (Vinter & Perruchet, 2000; Amso & Davidow, 2012), there is growing evidence that implicit learning does improve with age (Vaidya, Huger, Howard & Howard Jr, 2007; Janacsek, Fiser, & Nemeth, 2012; Lukács & Kemény, 2014). Since SL involves implicit learning, we may expect it to show a similar developmental trajectory and improve with age across modalities (Misyak, Goldstein & Christiansen, 2012).

A different prediction can be made when we consider the role of SL in language acquisition. Since infancy and early childhood are considered to be the prime-time for language learning (Birdsong, 1999), SL skills may be fully developed in infancy and not improve with age, a claim supported by the presence of SL in newborns (Bulf, Johnson, & Valenza, 2011). Such age invariance would be in line with Reber's claim that some implicit learning mechanisms are early-maturing. A recent fMRI study suggests that auditory SL may even become worse with age. McNealy, Mazziotta & Dapretto (2011) found an age-related decrease in sensitivity to weak statistical cues: younger children showed better sensitivity to low transitional probabilities compared to older children and adults. They suggest that this age-related decrease may help explain adults' worse language learning skills. Under this account, auditory SL skills may even show a negative age effect and deteriorate with age.

A third, more nuanced, prediction on the effect of age on SL takes into account modality-based differences. The fact that SL is found in multiple sensory modalities suggests it is domain general mechanism that works similarly on different kinds of input, linguistic and nonlinguistic (Saffran & Thiessen, 2007; Kirkham, Slemmer & Johnson, 2002; Saffran, Pollak, Seibel & Shkolnik, 2007). This idea receives support from the correlation between visual SL and auditory linguistic measures (Shafto et al., 2012). However, there is growing evidence of differences in learning between the auditory and visual domains that are more consistent with a modality-sensitive model of SL (Frost et al., 2015).

On an individual level, performance on auditory and visual SL tasks is not correlated, indicating they may tap onto different abilities (Siegelman & Frost, 2015). There also seem to be qualitative differences in learning across modalities, though studies differ in which modality shows better learning: Siegelman & Frost (2015) found that adults were better in the visual domain, while other studies found that adults showed better learning in the auditory domain (Conway & Christiansen, 2005; Saffran, 2002). This difference may also be modulated by constraints involving presentation rate: increasing stimuli presentation rate led to better learning the auditory domain, but worse learning in the visual domain (Emberson, Conway & Christiansen, 2011). One way of reconciling these findings is by characterizing SL as a domain general mechanism that applies similar computational principles to all input types but that is nevertheless modality-specific in that it reflects the particular constraints and perceptual biases imposed by different sensory input (Frost et al. 2015).

From a developmental perspective, age may affect learning differently in the visual and auditory domains. In particular, given its role in language acquisition, auditory SL may change less with age (or not at all) compared to visual SL. Such a finding would provide support for the modality-sensitive nature of SL. Yet there is currently very little empirical evidence to support any of these predictions or distinguish between them. To date, only few studies have examined the effect of age on SL, and they display a mixed pattern of results. Interestingly, some of the differences could be modality related.

In the visual domain, two studies that compared children and adults on the same task found no effect of age. Bertels, Boursain, Destrebecqz, & Gaillard (2015) report that children (aged 9 to 12) performed similarly to adults on a visual SL task. Jost, Conway, Purdy, Walk, & Hendricks (2015) found similar ERP patterns during a visual SL task among younger children (8-year-olds), older children (11-year-olds) and adults. Infants' visual SL also does not seem to change between 2- and 8-months (Kirkham et al., 2002). Overall, these findings seem to point to age-invariance in visual SL. However, they are based on quite small samples, examine a relatively narrow slice of development and compare groups of children in given ages rather than examining age as a continuous factor, all of which may mask the effect of age on performance (Arciuli & van Kos Torkisden, 2012; Bertals et al., 2015). Accordingly, a more comprehensive study of visual SL across development did find clear age-related improvement: Arciuli & Simpson (2011) examined visual SL in 183 children between the ages of 5 and 12 and found that older children showed significantly better learning. This single comprehensive study suggests that visual SL does in fact improve with age.

Crucially, even less work examined SL across development in the auditory domain, despite its postulated role in language acquisition. Only one study compared children and adults on the same auditory task and reported age-invariance: Saffran et al. (1997) found no difference in auditory SL between 6-year-olds and undergraduate students, with both age groups showing similar learning. This is somewhat surprising given that auditory grammar learning (AGL) improves with age, with adults showing better learning than six and nine-year-olds (Saffran, 2001). Studies on auditory SL during infancy also suggest age-related changes in early development. Specifically, infants' auditory learning biases change between 8- and 10-months (Emberson, Misyak, Schwade, Christiansen & Goldstein, 2015), and they show improved auditory SL abilities between 12- and 15-months (Gómez & Maye, 2005).

In sum, while Arciuili & Simpson's (2011) findings suggest that visual SL improves throughout development, the only study to compare auditory SL in children and adults found no difference between them. One possibility is that age does affect SL in the auditory modality as well, but that this pattern is not detected when using relatively small samples and comparing only one age group to adults (as in Saffran et al., 1997). Alternatively, it is possible that there are fundamental differences between visual and auditory SL that are also reflected in different developmental trajectories across modalities. In particular, SL may improve less in the auditory domain, or even show age invariance across childhood. These possibilities are hard to evaluate given the existing literature, as no study has examined auditory SL across development in a comprehensive way as was done in the visual domain by Arciuli & Simpson (2011).

The Current Study

To test the different predictions on the effect of age on auditory SL, we conducted the first large-scale, cross-sectional study of children's performance on an auditory SL task (ASL) across a wide age-range (5-12y). We ask whether performance is affected by age, and if so - then how: will auditory SL abilities improve across development as found in the visual domain, or will they show a different developmental trajectory?

Method

Our task was closely modeled on the classic segmentation task from Saffran et al. (1996). The task was completely computerized, with a human experimenter sitting by the children and providing them with verbal instructions.

Participants

115 children (age range: 5-12y, mean age: 8:3y, 63 boys and 52 girls). All children were visitors at the Bloomfield Science Museum in Jerusalem and were recruited for this study as part of their visit to the Israeli Living Lab. All participants received a small educational reward in return for participation. Parental consent was obtained for all children. All children were native Hebrew speakers, and none of them had known language or learning disabilities.

Materials

The auditory stimuli consisted of a synthesized "alien" language, containing 5 unique tri-syllabic words (made up of 15 different syllables): "*dukame*", "*gedino*", "*kimuga*", "*nalobi*" and "*tobelu*". All words were synthesized using the PRAAT software in order to control for syllable duration and frequency. Average word length was 850ms. The words were concatenated together in a semi-randomized order (with the constraint that no word will appear twice in a row) to create an auditory familiarization stream. In this stream, the transitional probabilities (TPs) between syllables within a word was always 1, while the TPs between words were 0.25 (because syllables were not repeated across words). The exposure phase lasted 2;20 minutes, with each word repeated 32 times. Importantly, there were no breaks between words and no prosodic or co-articulation cues in the stream to indicate word boundaries.

The test phrase included 25 two alternative forced-choice trials (2AFC), in which participants heard two possible "words" (separated by 500ms), and had to choose which one sounds more like the language they just heard. On each trial, participants heard a real word (like "*dukame*") either followed or preceded by a foil word. Foil words were constructed by taking the first syllable from one word, followed by the second syllable form another word, and the third syllable from a third word. Thus, each syllable in the foil words appeared in a similar position in real words, but with different surrounding syllables (for example, "*kilome*" or "*dubega*"). This created a difference in the statistical properties of the words and foils: while the TPs between every two adjacent syllables within a word are 1, the TPs between every two syllables in a foil test item are 0, as participants never heard these syllables one after the other during familiarization. If participants learn the statistical properties of the syllables in the stream, they should be able to distinguish between words and foils. The possible score on this task ranged from 0% accuracy (0/25 trails correct) to 100% (25/25 trails correct).

Procedure

Children were told they are about to hear an alien language, and were then exposed to the familiarization stream using isolating headphones. A picture of an alien in a spaceship appeared on the screen during the entire duration of the familiarization stream. Following exposure, children were told that they are about to hear an alien who is not a good speaker of the alien language, and that they must help him by telling him which of the two words he will say sounds more like the alien language they just heard.

The 25 test trails were presented to children in random order (with the constraint that the same word/foil will not appear in two consecutive trails). The order of words and foils on each trial was also randomized, so that half the trials were word-first trials (the word was heard before the foil) and half were foil-first trials (the foil was heard before the word). After hearing both possibilities, children were asked to press either '1' or '2' according to whether they thought the correct word was the first or the second they heard. In case children felt they didn't know the answer, the experimenter encouraged them to try and guess what sounds more familiar according to the alien language they heard. At the end of the task, the experimenter thanked the child for helping the alien learn the language, and showed them to the prize basket to pick their reward for participation.

Results

As a group, children showed learning in the auditory task with a mean accuracy score of 55%, which is significantly above chance ($t(114)=4.74$, $SE=1$, $p<0.0001$). Figure 1 shows children's mean performance on the task as a function of age (in half years): age seems to affect performance with older children showing better accuracy. To test for significance, we used a mixed-effect logistic regression model. Our dependent binominal variable was success in a single ASL test trial (see Table 1a). The model included fixed effects for age (in half years) and trial number as centered continuous factors, order of appearance in the test (word-first trials vs. general mean, deviation coding) and gender (females vs. general mean, deviation coding). Following Barr et al. (2013), the model had the maximal random effects structure that would converge, including random intercepts for participants and items, by-participant slopes for trial number and order of appearance, and by-items slopes for age and order of appearance.

The model showed that age had a significant positive effect on performance, with older children displaying better accuracy ($\beta=0.05$, $SE=0.02$, $p<0.05$). The effect of gender was not significant ($\beta=-0.05$, $SE=0.04$, $p>0.1$). Trial number was also not a significant predictor of accuracy ($\beta=-0.004$, $SE=0.005$, $p>0.1$), confirming that no learning (or unlearning) was happening during the test phase itself, despite the repetitions of both foils and words.

Interestingly, order of appearance in the test highly affected performance, with better accuracy on word-first trials (β=0.15, SE=0.03, p<0.001). Thus, children were better in trials where the real word was heard before the foil. Since the order of presentation was counter-balanced this could not reflect a preference for pressing 1 or 2. The advantage for word-first trials could reflect the "interval bias" found in 2AFC tasks in which the first word is used as a baseline for assessing the "wordness" of the next item (Einhom & Hogarth, 1981; García-Pérez & Alcalá-Quintana, 2011).

These results suggest that auditory SL improves with age. However, a somewhat different pattern emerged when we examined participants' performance in different age bins[1] (matched in number of participants, see Table 2).

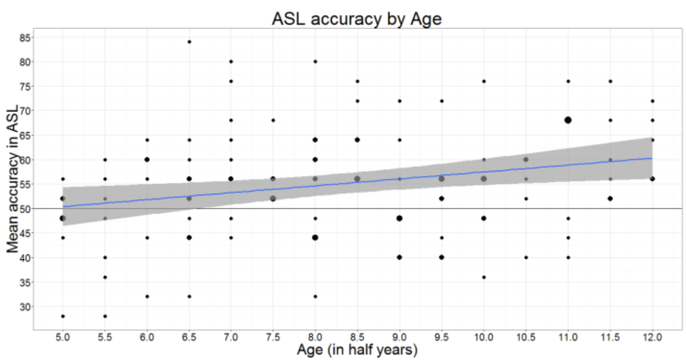

Figure 1: Accuracy in the task by age (in half years). *Each dot represents an accuracy score (ranging from 0% to 100%) shown by one (or more) participants in the relevant age range (size corresponds to the number of participants with this score). For example, some 8-year-olds were 60% accurate while others were 80% accurate. The plotted blue line represents the linear regression line, with the standard confidence interval appearing in gray. The black line represents the 50% chance level*.

Table 1a: regression model for ASL (ages 5-12y)

	Estimate	**Std. Error**	**z value**	***p*-value**
(Intercept)	0.198826	0.043712	4.548545	**< .001 *****
Age	0.056382	0.02222	2.537491	**< .05 ***
Trial Number	-0.00402	0.005519	-0.72823	> .1
Order of Appearance	0.156133	0.039387	3.964068	**< .001 *****
Gender	-0.05032	0.042881	-1.17336	> .1

Table 2: ASL Accuracy by Age Bins

	N	**Mean VSL score**	**p-value**
Age Group 5 to 6	21	**48%**	> .1
Age Group 6.5 to 8	38	**56%**	**< .01 ****
Age Group 8.5 to 10	32	**55%**	**< .05 ***
Age Group 10.5 to 12	24	**59.5%**	**< .001 *****
All Children	115	**55%**	**< .001 *****

[1] We applied age bins only for means of presenting the data, yet used age as a continuous factor (in half years) in all our analyses.

We found that children in the youngest age group (ages five to six) did not show significant learning: unlike children in all other age groups, their performance did not differ from chance (M=48%, t(20)=-0.786, SE=2, p=0.44). This is also reflected in Figure 1, which shows that the majority of children aged 6 and below are performing at chance level (we will address this issue in the discussion).

We therefore conducted a second analysis to see if the effect of age on performance was driven by the inclusion of the youngest age group that showed no learning. We ran an additional model with a similar effects structure using the data obtained only from children older than 6, excluding the 21 children in the youngest age bin (Table 1b).

As suspected, the effect of age disappeared in the new model: without the youngest group of children, who showed chance-level performance, age was no longer predicative of accuracy (β=0.02, SE=0.02, p>0.1). That is, auditory SL did *not* show an improvement between the ages of 6.5 and 12, a significant developmental window. In line with previous reports (Saffran et al. 1997), this finding suggests that auditory SL is a rather stable, age-invariant capacity across childhood, at least after age 6.

Table 1b: regression model for ASL (ages 6.5-12y)

	Estimate	**Std. Error**	**z value**	***p*-value**
(Intercept)	0.266438	0.051252	5.198571	**< .001 *****
Age	0.022181	0.029971	0.740099	> .1
Trial Number	-0.00586	0.006286	-0.93166	> .1
Order of Appearance	0.159104	0.04499	3.536454	**< .001 *****
Gender	-0.04966	0.047842	-1.03799	> .1

Discussion

Our study shows that auditory SL did not improve with age after excluding the youngest age group of children (aged 6 and below), who performed at chance. Even though we initially found an age-related improvement in the task, our second analysis showed that this effect was driven by the youngest group of children, who simply did not show learning. After excluding this group, we found no significant change in children's auditory SL skills across development (between the ages of 6.5 to 12y). This result differs from the findings of Arciuli & Simpson (2011), who reported an improvement with age in the visual domain, and is in line with Saffran et al. (1997), who found age-invariance in the auditory domain when comparing six-year-olds to adults on a similar auditory segmentation task. That is, auditory SL, unlike visual SL, seems to be age invariant.

The finding that auditory SL is age-invariant across development is supportive of Reber's claim that some implicit learning mechanisms, presumably those that are used early in life may not be affected by age. The age-invariance seen in this study is consistent with the postulated role of auditory SL in language acquisition (e.g., Saffran et al., 1996), and the fact that language learning skills are at their prime during infancy and early childhood (Birdsong, 1999).

Our findings also points to modality-based differences in the developmental trajectory of SL abilities: unlike visual SL (Arciuli & Simpson, 2011), auditory SL did not change during development. This finding also strengthens the claim that the improvement reported in the visual domain by Arciuli & Simpson (2011) reflects true changes in SL, and is not merely the result of general improvement in other cognitive abilities related to task performance (e.g., attention, working memory). If the improvement in visual SL was caused by the maturation of other cognitive skills, we would expect a parallel pattern across domains, which is not the case. Taken together, our study supports modality-sensitive models of SL where the type of stimuli has an effect on learning (Frost et al., 2015).

Importantly, not enough is known about the nature of the difference between modalities as no direct comparison was made between auditory and visual SL in children using tasks with similar input statistics. Our task differed from that of Arciuli & Simpson (2011) in having five words compared to four visual triplets: while it is possible this affected the results, it is unlikely to have caused the effect of age to disappear. If anything, the boundaries between words are more marked in our study (because of the larger number of words). Nevertheless, to comprehensively assess possible modality-based differences in the developmental trajectory of SL skills, a direct comparison should be made between auditory and visual SL skills using similar populations, similar designs, similar statistical properties of the input, similar exposure and preferably the same children performing both tasks to detect correlations in learning across domains.

Our results are limited in an important respect: we found that children below 6 did not show any explicit learning in our task. Since infants do exhibit significant learning in ASL when using more implicit tasks (e.g, Saffran et al., 1996), it is possible the youngest children are capable of learning the auditory regularities but fail in manifesting this knowledge using more explicit tasks. Children under six may be too young to exhibit their implicit knowledge and/or to understand the verbal instructions given to them. Indeed, studies show that it is significantly harder for young children to learn an artificial language in laboratory settings, resulting in inferior performance overall (Ferman & Karni, 2010; Folia et al., 2010). Consequently, more implicit tasks should be used in future studies with younger children (before age 6).

Such findings – from early childhood – are crucial in understanding the developmental trajectory of auditory SL. This time period is the one in which children's language skills develop the most, and in which many other cognitive changes occur. It could be that auditory SL skills only improve until a certain period in childhood and remain steady from that point on. In other words, auditory SL may be fully developed by the first year of life, or may develop only during early childhood.

Conclusions

The results of this study suggest that auditory statistical learning does not improve with age during childhood, but is at adult capacity by age six. This finding suggests that auditory SL is an early-maturing and stable capacity in an individual. However, more research is required to (a) examine whether SL abilities in different modalities are affected differently by age, and (b) examine the developmental trajectory or SL from infancy to early childhood. Future work should compare the developmental trajectories of auditory and visual learning across development using similar tasks, and studies with younger children should employ more implicit tests.

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