4-month-olds Discover Algebraic Patterns in Music That 7.5-month-olds Do Not

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Abstract

The recent language acquisition literature has revealed powerful, domain-general learning mechanisms that rely on frequency and distributional properties of the input. A second set of research investigates generalization of learned patterns to new input. The relationship between these two bodies is not entirely clear. The present paper demonstrates that the latter mechanism appears to be domain-general as well, although, in the domain of musical chord sequences, there is a decrease in sensitivity to algebraic patterns between 4 months of age and 7.5 months of age. We show that 4-month-old infants can discriminate three-chord patterns based on their AAB or ABA structure after being exposed to a set of patterns representing one of the structures. By 7.5 months, however, infants do not seem to make the discrimination, probably due to their experience with musical sequences, in which repetition plays less of a role than tonal structure.

Introduction

Until recently, it was thought in language acquisition circles that the linguistic input a child receives is much too impoverished to provide her with the rich structure necessary to support observed production; that is, unless her genetic endowment provided an intricate scaffolding in the form of a Universal Grammar. On this view, much of the structure was built in, and all that remained was for a set of "switches" to become "triggered" by a few relevant examples.

It has now become clear that the linguistic input available to the child is vastly richer in information than previously believed. Much of this information exists as statistically reliable relationships among components of the input. This discovery has led to a burgeoning line of research in cognitive science, dedicated to examining a phenomenon labeled "statistical learning". One of the questions raised by the research on statistical learning is whether the same learning mechanisms apply across a range of domains and not just to language. The first question directly addressed by the experiment discussed here is whether the ability to make a generalization based on the abstract relational properties contained in an input set is unique to the domain of language, or whether it might be applied to analogous structure in musical input.

In order to discover statistical structure pertaining to abstract relational properties across the units in an input set, the learner must be inclined to analyze the input with respect to that particular unit. Music, like language, possesses a hierarchical structure, with units of different sizes nested within each other. Whereas in language the set of nested units might include phonemes, syllables and words, in music the units are notes, chords and phrases of various lengths. The input can contain structure at each of these levels; which level is the most salient will depend in part on the expectations of the listener. The second question addressed by this paper is whether, over time, a learner's expectations will come to correspond to the sorts of structure frequently encountered in a particular domain.

What is Statistical Learning?

To begin with, a brief discussion of the general cognitive ability in question is warranted. The phenomenon referred to as "statistical learning" (SL) has been of great interest to those studying cognitive development over the past decade. Broadly construed, SL refers to an unsupervised learning process wherein an organism extracts frequency, probability and/or distributional information from a set of input, thereby structuring perception of the input.

One set of SL studies concerns subjects' ability to parse input into constituent elements – a critically important skill for learning language. Saffran, Newport and Aslin (1996) and Saffran, Aslin and Newport (1996) familiarized adults, pre-school-aged children and 8-month-old infants with a continuous stream of syllables comprising tokens of several back-to-back, three-syllable pseudowords drawn from a given "vocabulary". When tested, all three groups could discriminate between constituent strings and those that occurred in the input stream, but which spanned word boundaries. In order to successfully perform this discrimination, subjects had to track some sort of frequency information in the familiarization stream. Further research suggested that the relevant information might be the set of transitional probabilities between elements (syllables and/or segments), and not simple pattern frequency (Aslin, Saffran, & Newport, 1998).

Maye, Werker and Gerken (2002) have observed infants making use of a different kind of frequency information. They show that infants make use of distributional properties of the input, appearing to form either one or two phonetic categories depending on whether instances of a consonant in a familiarization stream have a unimodal or bimodal distribution with respect to voice onset time.

A second set of research examines learners' abilities to detect relational properties in the input, and to discriminate new items that contain the same relational properties from those that violate those relations. Gómez and Gerken (1999) show that infants can learn rather complicated artificial grammars with relatively little exposure, generalizing "rules" to entirely novel strings. Marcus, et al. (1999) show that 7.5-month-old infants can detect higher-order, "algebraic" structure in a series of trisyllables, discriminating an AAB structure from an ABA structure.

It is not clear how, or to what extent, this last type of "rule-learning" is related to the type of statistical learning that relies on frequency information. In particular, voice onset time is a very low-level property, closely tied to the surface form of a token. Similarly, transitional probabilities, though relational in nature and somewhat less closely tied to surface forms, nonetheless involve specific tokens. Even the kind of relational dependency explored by Gómez and Gerken (1999) involves relations between specific elements. The commonality among instances of an AAB pattern, regardless of the specific elements, is a strictly relational one on the other hand, and seems very distant from surface form.

Marcus, et al. (1999) invoke variables in their explanation of this phenomenon. One could imagine, however, that all that is necessary to detect an AAB pattern is the ability to judge whether two successive items are the same or different. If one simply stores a sequence of "sames" and "differents" relative to pauses, the problem is not qualitatively so different from one where surface form is important.

Is SL Specific to Language?

The ability to segment a stream of information into constituent units is undeniably necessary for the learner of language; lumping together similar tokens into linguistic categories greatly increases processing efficiency, while making generalizations about relational properties is the basis of syntax. Frequency and distributional information clearly provide useful information that could assist the infant in the first two tasks and possibly also the third. An obvious question, though, is whether these abilities are uniquely applied to language, or whether they are more general cognitive phenomena. If the discovery of abstract relationships is qualitatively different from statistical learning about particular units, the question of domain-specificity might have a different answer for each of the two cases.

Several experiments have demonstrated that SL-based segmentation occurs not only with linguistic stimuli, but also with tone stimuli and visual stimuli. Saffran, Aslin and Newport (1999) substituted a tone for each syllable in the familiarization streams used in the original experiments, and demonstrated that all three groups learned the tone-word boundaries just as easily as they had learned the syllable pseudoword boundaries. Fiser and Aslin (2002) and Kirkham, Slemmer and Johnson (2002) found similar results, with adults and infants respectively, using sequentially presented shapes. Learners can also segment a visual scene into statistically reliable elements; Fiser and Aslin (2001, 2002) combined spatially arranged base pairs of shapes onto a grid, and showed that both adults and infants could discriminate constituent base pairs from pairs that appeared in the input only by a chance alignment of two base pairs.

An alternative approach to the question of specificity to language involves learners that do not use language. Hauser, Newport and Aslin (2001) and Toro and Trobalon (2005) familiarized tamarind monkeys and rats, respectively, with the original stimuli from the 1996 segmentation study. They found that these animals, too, could discriminate coherent from incoherent strings. Taken together, these two collections of findings provide strong evidence that at least the ability to segment using statistical cues is not part of a modular language faculty, but rather a general cognitive phenomenon.

It may be the case, however, that while a segmentation ability is domain-general, the abstraction ability observed by Marcus, et al. (1999) is reserved for language alone. This would be a surprising result, in light of the wide range of domains in which humans make abstract analogies (e.g. Forbus, et al., 1998; Perott, Gentner & Bodenhausen, 2005); nonetheless, it is the very view held by Fernandes, et al. (2005). They substituted tones for the syllabic elements from Marcus, et al. (1999), and found that 7.5-month-old infants no longer appeared to detect the algebraic forms. They claim that, while segmenting a stream of input using statistical information appears to be a domain-general ability, detecting abstract structures such as AAB is not statistics but rule-learning, and is preferentially tuned, perhaps even exclusive, to linguistic structures.

It is possible that the discrepancy between syllable sequences and tone sequences found by Fernandes, et al. is not due to a difference in learners' abilities to discover abstract relations in the input, but rather is due to a difference in their willingness to consider a specific type of relation at a certain level in the hierarchy. In particular, it may be that after a certain amount of experience with a domain where a certain kind of relation does not occur systematically, learners might lose a degree of sensitivity to that type of relation.

Input-dependent shifts in processing

A loss of sensitivity to unsystematic characteristics of the input is would not be unprecedented. For example, Werker and Tees (1984) found a loss of sensitivity to those phonetic contrasts that did not occur systematically in the languages of infant perceivers. There are examples in the domain of music as well. Saffran and Griepentrog (2001) found that while 8-month-old infants readily make use of statistically reliable absolute pitch cues to segment atonal tone streams, adults do not succeed in segmenting these tone streams. Adults will, however, make use of relative pitch cues to segment atonal tone streams. Interestingly, Saffran (2003) has shown that when tone streams are constructed within a major key, adults can make use of absolute pitch cues or relative pitch cues equally well. It is possible that the reason for this discrepancy is that when absolute pitches reoccur in the context of a tonal key, they can be differentiated not only on the basis of their absolute pitch, but also on the basis of their pitch relative to the tone center of the key.

In any case, a shift in musical cognition from a focus on local properties to a focus on more global properties makes adaptive sense. In the case of phonetic discrimination, the loss of sensitivity to non-native contrasts can be attributed to a need to spend cognitive resources on determining meaning in language, rather than on making fine-grained perceptual discrimination that are irrelevant to the identity of a word. In other words, a priority is placed on more global, semantic distinctions, at the expense of local, surface perception. In music, the specific key of a melody does not change its identity; instead, determining whether a person is humming "Happy Birthday" or "The Volga Boat Song" requires detection of the relative pitch structure. If either of these melodies is transposed, it will still be recognizable, but if any interval is altered, it will be immediately noticed.

Music is in some sense two-dimensional, containing pitch and time information. Both of these dimensions contain both atomic and relational properties. The evidence for a developmental shift from a focus on absolute pitch to a focus on pitches in relation to each other and within a scale structure is evidence of a shift of perceptual emphasis toward relational properties along the pitch dimension.

It would not be surprising if a similar shift were found in perception along the temporal dimension. In fact, Hannon and Trehub (2005) found a loss of sensitivity to metric discrepancies, between infancy and adulthood, when the metric ratios that were used deviated from the small integer ratios commonly found in Western music. This finding suggests that while infants are sensitive to fine-grained temporal variation, adults tend to assimilate durations into a relational scheme.

Perhaps the most important cognitive process with respect to the temporal dimension of music is the grouping of events into larger constituents. In this, music is similar to language. Successful temporal grouping can greatly reduce the memory load required to "appreciate", and especially to reproduce, the music. A potential consequence of this grouping, however, is a loss of sensitivity to group-internal structure.

The present study may provide some insight into changes in the perception of music within the first year of life. Of particular interest is the relationship between learners' expectations about structure in particular domains on the one hand, and the kinds of structures reliably found in those same domains. Specifically, our prediction is that learners with less experience with music will readily detect arbitrary structural patterns in music, while more experienced learners will be less able to quickly pick up on structures that are not typically found in the music they have had experience with.

Method

Participants

Twenty-seven infants, recruited from the Tucson area, participated in this study. Of those, nine were between four months and four months and two weeks old (mean age = 19 weeks), and eighteen were between seven and eight months old (mean age = 32 weeks). Four of the 4-month-olds and eight of the 7.5-month-olds were female. Data from three additional 4-month-olds and six additional 7.5-month-olds were excluded from analysis due to these infants' failure to complete the required number of trials.

Stimuli

Familiarization trials contained eight distinct three-note chords, half major triads and half minor triads, randomly sampled without replacement from among the twelve roots between middle C and the B above it. The set of chords was pseudorandomly divided in half, four labeled "A" and four labeled "B", with the following constraints: major and minor triads were distributed evenly, at most one of the three notes was contained in both of any possible pair of A and B elements, and of the sixteen possible pairs of A and B elements, the root of the B chord was the higher of the two half the time, and the lower of the two half the time. Each chord was 625 msecs long.

Three-chord phrases of the forms $A_iA_iB_j$ and $A_iB_jA_i$ were then constructed, such that all sixteen combinations of A and B elements were represented in each type. Two familiarization trials were constructed, one containing each pattern. Each trial contained three blocks, each of which contained a different randomized order of the sixteen chords. The same randomized orders, with respect to the combinations of A and B elements, were used for each pattern. There were no pauses between chords within a phrase, and 625 msecs of silence between phrases. An entire familiarization trial lasted two minutes.

Four additional triads were generated, two major and two minor, using the four remaining root notes. These chords made up the test trials. One each of the major and minor chords was assigned at random to the "A" category, the other two to the "B" category. Once again, in two of the four possible combinations of A and B triads, the root of the B chord was higher than that of the A chord; in the other two it was lower. Four AAB phrases and four ABA phrases were created. Two AAB and two ABA test trials were built from these phrases, such that each phrase occurred three times per trial, orders randomized by block and matched between AAB and ABA trials. The tempo and spacing was identical to that in the familiarization trials.

No two three-chord phrases, across familiarization and test trials, contained exactly the same relative pitch patterns.

Procedure

The headturn preference procedure (Kemler Nelson, Jusczyk, Mandel, Myers, Turk, & Gerken, 2005) was used. Infants were seated on a parent's lap in a small room. The parent listened to popular music through headphones, in order to mask the music heard by the infants and to prevent inadvertent influence on the infant by the parent. Parents were instructed that they could end the study at any time by signaling to the observer via the camera.

During the familiarization phase, a light directly in front of the infant flashed until the observer judged the infant to be looking at it, at which point a light on the left or right would begin flashing. When the infant looked first at the side light and then away for two consecutive seconds, the center light would flash again, and the cycle would begin again. This continued for the duration of the familiarization music, which played uninterrupted for two minutes. Note that in this stage there was no correspondence between infants' looking behavior and the music.

After the familiarization sequence ended, the test phase began immediately. The flashing lights behaved the same way, except that now the sound was contingent on the infant orienting to a side light. Each time a side light began flashing and the infant oriented toward it, one of the four test trials would play, continuing until either the infant looked away for two consecutive seconds or 30 seconds had elapsed. Each infant heard three blocks of test trials. Each of the four trials occurred once per block, the order randomized on-line within each block.

The observer controlling the presentation of the music sequences could not hear anything happening within the booth, and so was blind to the category of each test trial. The computer automatically recorded the looking time for each test trial.

Results

Criteria for Inclusion

In order for the infant to determine whether the pattern from familiarization was being heard in a given test trial, she had to hear at least one complete phrase. Therefore, if any trial was shorter than two seconds, it was not included in the analysis. This is standard practice in headturn preference experiments. If any infant did not have at least three trials of each type over two seconds, that infant's data was excluded from the analysis entirely.

Analysis

Two mean looking times were computed for each subject, one for consistent pattern test trials and one for inconsistent pattern test trials. Paired samples t-tests were conducted for each age group. The 4-month olds showed a significant preference for the test trials that were inconsistent with their familiarization condition ($t(8) = 2.77$, $p=0.02$, two-tailed). Eight of the nine infants of this age showed this pattern. The 7.5-month-olds did not have a significant preference ($t(17) = 0.33$, $p=0.74$, two-tailed). Seven of the eighteen infants of this age showed a preference for inconsistent trials. A chi-square test using the number of infants having longer listening times for consistent trials versus inconsistent trials was performed to contrast the two age groups, and it was highly significant ($\chi^2(27)=6.08$, $p=.01$).

Discussion

The preceding experiment contains two important findings. First, the ability of 4-month-olds to discriminate old and new algebraic patterns suggests that the ability to make generalizations based on these patterns is not specific to language. In fact, the infants that we have shown to possess this ability with respect to music are a full 3.5 months younger than the youngest infants that have demonstrated the ability with respect to language.

The second interesting finding is that, at least with respect to algebraic patterns in sequences of three musical chords, it appears that infants' readiness to categorize musical phrases based on the abstract relationships among component chords decreases somewhat between 4 and 7.5 months of age.

Interpreting the Performance Decline

There are a number of possible interpretations of this finding. It may be that the two age groups perceive the three-chord phrases with a different level of detail. If the 4-month-olds are registering only the rise-fall contours of the phrases, then the discrimination task might simply be a matter of detecting rise-fall patterns that have been encountered before. If, on the other hand, the 7.5-month-olds are noticing specific intervals within the phrases, they may be distracted from the properties shared within and between familiarization and test. A possible source of evidence against this hypothesis comes from Trehub, Thorpe and Morrongiello (1987), who show that 10-month-olds can group melodies based on common contour, even when specific intervals are variable. In fact, performance in this task was as good as in a task where intervals were not variable. It should be noted, however, that in that experiment, melodies consisted of single tones, as opposed to chords, and could be attributed to a single, tonal key. The aforementioned results are consistent with an interpretation where infants are perceiving intervals and contours simultaneously, and so the increased interval complexity in our experiment could conceivably detract from processing of contour.

Another potential source of distraction for the 7.5-month-olds (not mutually exclusive with the one discussed above) might be the pseudotonality of the stimuli. The individual A and B elements in our experiment were major and minor triads, each of which contained consonant intervals within it. Horizontally, however, the chords did not fit into a single scale structure; triads based on all 12 semitones in the chromatic scale were used, and so no single key across chords would be identifiable. This non-tonality is a characeristic of the stimuli used by Fernandes, et al. (2005) as well.

Trehub, Schellenberg and Kamenetsky (1999) report that 9-month-olds detect mistuned notes in unequal interval scales (such as those used in traditional Western music), but not in equal interval scales (of which the 12 tone chromatic scale is one), indicating that infants can make use of global scale structure to organize their perception of music. If this ability is in place by 7.5 months, the older infants in our experiment could be attempting in vain to find the scale structure across entire trials, which might keep them from noticing the relational structure that exists within phrases. If 4 months olds are not snared in such a way, it may be that they have not yet begun to perceive music for its scale structure, or it may be that their smaller working memory capacity leads them to focus on smaller units. On this hypothesis, it would be interesting to test 7.5-month-olds on strictly tonal stimuli. Perhaps once the global structure is apparent, they will have more resources to direct at local structure.

Finally, it could be the case that the two age groups are simply focusing on units of a different size. For example, while the 4-month-olds might be treating each chord as an atomic unit, and phrases as compositional, 7.5-month-olds could be treating phrases as atomic and perceiving entire trials as compositional melodic units. Drake and Bertrand (2001) suggest that a universal characteristic of perception of temporal grouping might be to place homogenous rhythmic textures together into a single "object". Our stimuli had two levels of rhythmic homogeneity: one within phrases and one across phrases. Every chord within a phrase was the same length, and spacing between chords was identical, perhaps motivating a treatment of phrases as units. This might have been the grouping used by 4-month-olds. However, each phrase was also the same length, with identical spacing between phrases, potentially motivating a grouping of phrases into larger phrases. It may be that the 7.5-month-olds were perceiving this higher-level grouping. In our experiment, there are two types of test trials with respect to composition of individual phrases, but if phrases are atomic, then the two types of test trials are identical with respect to patterns across phrases.

One possible explanation for the discrepancy in unit size is a difference in working memory capacity, combined with a general preference for focusing on the highest-level unit available. It is unlikely that 7.5-month-olds generally cannot detect commonalities of within-phrase patterns, however, in light of numerous experiments that show an ability of infants this age and older to detect, for example, commonalities in pitch contour between phrases (e.g. Trehub, Schellenberg and Kamenetsky, 1999). Instead, there may be something about the particular property of interest in our experiment that causes 7.5-month-olds to ignore commonalities between non-identical phrases. Perhaps something about the infants' experience with music has led them to the conclusion that, with respect to algebraic identity, it is entire phrases that are important. Indeed, children's songs contain quite a bit of repetition of entire phrases, both immediately and with intervening phrases (i.e. of the AAB and ABA variety), but within phrases, repetition of single notes is idiosyncratic. For example, think about the song "Three Blind Mice". It contains several different phrases, each of which is repeated two or three times. The entire song could be described by the pattern AABBCCCA. This structure is immediately apparent to a listener. Where there is repetition of single notes, on the other hand, it is not especially striking. Perhaps with their greater exposure to music, 7.5-month-olds have learned to ignore algebraic patterns of single notes or chords.

Innate vs. Learned Constraints and Biases

The preceding experiment gets at a question that is fundamental in linguistics, and cognitive science generally. It is often the case that, upon discovering some cognitive discrepancy of one sort or another, whether it is a preference for certain types of structure, a difference in processing between language and another domain, or an apparent specialization of function in the brain, we conclude that the discrepancy reflects humans' innate endowment. However, we also need to consider that the discrepancy in cognition could have arisen because of a discrepancy in the environment. On occasion, examination of a population that has had a lesser degree of exposure to the portion of the environment in question could reveal that a cognitive discrepancy, thought to be of the first type, is in fact of the second.

We have shown that parallels in learning between language and a non-linguistic domain exist not only in segmentation, but also in a task that requires detection of relational properties. With respect to the particular task involved, however, these parallels begin to fade with age. Our tentative conclusion is that this developmental shift is due to differences in the structures found in the two environmental domains. However, further research is needed to convincingly determine whether the reason for this fade is in fact due to differentiation of the structures found in the two input environments, or whether there may be some other reason for the performance decline.

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