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Separable developmental trajectories for the abilities to detect auditory amplitude and frequency modulation

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Abstract

Amplitude modulation (AM) and frequency modulation (FM) are inherent components of most natural sounds. The ability to detect these modulations, considered critical for normal auditory and speech perception, improves over the course of development. However, the extent to which the development of AM and FM detection skills follow different trajectories, and therefore can be attributed to the maturation of separate processes, remains unclear. Here we explored the relationship between the developmental trajectories for the detection of sinusoidal AM and FM in a cross-sectional design employing children aged 8–10 and 11–12 years and adults. For FM of tonal carriers, both average performance (mean) and performance consistency (within-listener standard deviation) were adult-like in the 8–10 y/o. In contrast, in the same listeners, average performance for AM of wideband noise carriers was still not adult-like in the 11–12 y/o, though performance consistency was already mature in the 8–10 y/o. Among the children there were no significant correlations for either measure between the degrees of maturity for AM and FM detection. These differences in developmental trajectory between the two modulation cues and between average detection thresholds and performance consistency suggest that at least partially distinct processes may underlie the development of AM and FM detection as well as the abilities to detect modulation and to do so consistently.

Keywords

Amplitude Modulation (AM); Frequency Modulation (FM); Perceptual Development; Adolescence; Temporal Processing; Performance Consistency

1. Introduction

The ability to detect fluctuations in the amplitude and frequency of sounds is considered important for normal auditory processing, including the perception of speech (Shannon et al., 1995; Stickney et al., 2005; Zeng et al., 2005). This ability improves over the course of normal development for both types of modulation (Hall and Grose, 1994; Sutcliffe and Bishop, 2005). Here we explored the relationship between developmental trajectories for the

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detection of amplitude modulation (AM) and those for frequency modulation (FM) by evaluating performance on these two tasks in the same sets of listeners in a cross-sectional design using two indices of performance – mean detection threshold (average performance) and within-listener performance variability around the mean threshold (performance consistency). The relationships among these trajectories are of particular interest because evidence for distinct maturational rates between AM and FM detection on either measurement index would suggest that the mechanisms underlying the development of the capacity to detect these two types of modulation are at least partially separable. In addition, different developmental courses between average performance and performance consistency on either task would imply that partially distinct processes govern the development of these two aspects of performance.

Separate reports on the maturation of sensitivity to the presence of FM and AM suggest that average performance on both of these tasks reaches adult levels before 10 years of age, but these developmental time courses have been more firmly established for FM than for AM detection. Sutcliffe and Bishop (2005) and Dawes and Bishop (2008) conducted two large scale studies on the development of the ability to detect FM. Their results indicate that average performance on this task matures by 7 years of age for modulation rates > 20 Hz and by 9–10 years of age for slower rates. Hall and Grose (1994) conducted a smaller scale study of the development of AM detection for modulation rates ranging from 5 to 200 Hz. They found that the AM detection thresholds of children younger than 7 years of age were higher than those of adults, while the thresholds of 9–10 year olds were adult-like. Lorenzi et al. (2000) also reported adult-like AM detection for AM rates of 4 to 1024 Hz in a single group of six children with a mean age of 11;6 (11 years and 6 months), but because those children ranged in age from 8;5 to 14;7 years, it is difficult to determine from that data set when the adult level of performance was attained. Thus, while average performance on both FM and AM detection has been investigated using developmental designs, these studies were based on considerably larger groups of children for FM than for AM detection and were conducted on different individuals, with somewhat different assessment procedures, for the two tasks. These differences complicate comparisons of the maturational rate between these skills.

The development of performance consistency has been examined previously for FM, but not AM detection. Several groups have used measures of performance consistency as a means to help determine what is changing with development on auditory tasks (Allen et al., 1989; Dawes and Bishop, 2008; Moore et al., 2008; Wightman et al., 1989). Underlying the use of consistency measures is the assumption that they reflect the status of general non-sensory factors that influence performance on psychophysical tasks, such as selective attention. Therefore, when considered in the context of the relatively early maturation of the auditory periphery, observations that average performance improved with age in parallel to consistency have been interpreted as indicating that auditory development in school-age children primarily reflects the maturation of non-sensory processes (e.g., Wightman et al., 1989, Moore et al., 2008). For FM detection, however, Dawes and Bishop (2008) reported a dissociation between the development of average performance and performance consistency. For all 3 tested modulation rates, age significantly accounted for unique variance in average performance, beyond the contribution of performance consistency. This result suggests that the maturation of performance on FM detection may not derive solely from general non-sensory factors and that the developmental courses for average performance and performance consistency may be dissociated. Performance consistency was not evaluated in either previous study of the development of AM, thus precluding any comparison of developmental trajectories between AM and FM detection on this measure, or between average performance and performance consistency on AM detection itself.

In the present investigation we measured both AM and FM detection in the same samples of younger (8–10 year old) and older (11–12 year old) children and adults, using the same methodology to assess both abilities, and compared the developmental trajectories of both average performance and performance consistency between the two tasks. For each task, we used a carrier that is known to yield near-optimal performance (and relatively low variability) in adults on that task, namely a broad band noise for AM (Eddins, 1999; Fromby & Muir, 1988) and a pure tone for FM. This choice allowed us to compare the developmental trajectories leading to optimal detection of each modulation cue and furthermore to compare the outcomes to those of previous developmental investigations of either AM (Hall and Grose, 1994; Lorenzi et al., 2000) or FM (Dawes and Bishop, 2008) detection in which similar carriers were used. The results suggest that different mechanisms may be responsible for the maturation of the ability to detect AM and FM and that the ability to detect modulation may develop independently of the ability to use it consistently.

2. Materials and Methods

2.1 Listeners

A total of 34 listeners ranging in age from 8 to 27 years participated in this study. The children all passed a hearing screening at the standard audiometric frequencies from 0.5 to 4 kHz. The adults reported having normal hearing. The listeners were divided into three groups: a younger child group ($n=12$) aged 8;0 – 10;11, an older child group ($n=11$) aged 11;00 – 12;11, and an adult group aged 17–27 years ($n=11$). The age ranges of the child groups were selected so as to give equally sized groups. None of the listeners had any prior experience with auditory psychophysical tasks. Children were paid for their participation and were recruited with flyers posted around the Northwestern University Evanston campus and the surrounding neighborhoods. Adults received partial course credit for participation. All listeners (or their legal guardians) gave informed consent to participate in the study. All aspects of this study were approved by the Northwestern University Institutional Review Board.

2.2 Tasks, stimuli and procedure

An adaptive 3-interval, 3-alternative forced-choice oddball detection task was used to measure detection thresholds for both AM and FM as well as individual listener performance consistency around these thresholds. Sounds were embedded in a video game (CAPE, IHR, Nottingham, UK). In the game, on each trial, three cartoon animals appeared on a computer screen (cats for FM, mice for AM). Each animal appeared to make a sound in turn and the participants were asked to use a computer mouse to select the animal that made the target sound. The target – ‘odd one out’ -- sound was modulated with either AM or FM in different sets of trials, whereas the other two sounds were unmodulated standards. The inter-stimulus interval was 500 ms. Participants were instructed to select the modulated, ‘odd sounding’ sound or ‘the sound that was not like the others.’ The modulation depth of the targets was varied adaptively using a 3-down/1-up staircase procedure in which modulation depth decreased following 3 consecutive correct responses and increased upon an incorrect one. Reversal values, that is modulation depths on the trials in which the direction of the adaptive track changed from decreasing to increasing or from increasing to decreasing, were noted. For each listener, reversal values from all runs of a particular modulation rate and type (excluding the first 3–4 reversals per run) made the final data set subsequently used to calculate the threshold and consistency performance indices (see below). Feedback was provided for both correct and incorrect responses. Three runs of 40 trials were administered for each of the conditions described below. Ten percent of trials (randomly selected) were ‘catch trials,’ in which the modulation depth of the target sound

was double that of the previous trial. Performance on those trials was used to determine whether participants were attending to the task.

Stimuli

Amplitude modulation: Following previous developmental studies of AM detection in children with and without dyslexia (Hall and Grose, 1994; Lorenzi et al., 2000), for the AM task, the carrier was a 0.5-s 8-kHz low-pass noise. Target sounds were sinusoidally modulated at 8, 64, and 125 Hz during separate runs. The initial modulation depth was 75%. The step size was 2 (modulation depth was divided/multiplied by 2) until the fifth reversal and was subsequently reduced to 1.41. All sounds were presented at 70 dB SPL.

Frequency modulation: Also following previous investigations of FM detection in children (Boets et al., 2006; Talcott et al., 2000), for the FM task, the carrier was a 1-s 1-kHz tone. Target sounds were sinusoidally modulated at 2, 20 or 240 Hz during separate runs. The initial modulation depth was 10% (i.e., the instantaneous frequency of the stimulus varied from 0.9 to 1.1 kHz around the 1-kHz carrier). Modulation depth was divided by 2 following every correct response until the first error occurred. Subsequently, the 3 down/1 up staircase was applied with a step size of 1.41. Sound presentation level was 70 dB SPL.

Procedure—Child participants were tested in two sessions, typically conducted 1–3 weeks apart, as part of a larger test battery that included reading and cognitive tests as well as additional psychophysical tests of frequency and intensity discrimination. They were tested on the AM and FM tasks in separate sessions. Adults were tested on the AM and FM tasks only and completed the testing on both tasks during a single session. Half of the children and adult participants performed the AM task first while the other half performed the FM task first. Within each task (AM, FM), the order of modulation rates was randomized. All three runs of each rate were performed before proceeding to a different rate. Prior to the beginning of testing on the first rate on each task participants were required to score at least 80% correct on a series of ten non-adaptive sample trials. For both the AM and FM tasks, the modulation depth of the test tones during those trials was 100%.

Due to time constraints, two adults and one child were not tested on any of the FM rates and two children were not tested on AM with modulation rates of 8 and 64 Hz. Two additional adults and two children were not tested on FM detection with the 240-Hz modulation because they found the tones modulated at this rate to be annoying and asked to stop the test.

2.3 Measures of psychophysical performance

The reversal values contained in the final data set (excluding the first 3–4 reversals per run) of each listener were used to derive two measures of performance for each task and each modulation rate— average performance and performance consistency. Average performance was defined as the within-listener mean of all of the reversal (modulation depth) values in the final data set for a particular condition. Performance consistency was defined as the within-listener standard deviation (SD) of the same reversal values.

2.4 Outlying data points

Prior to statistical analysis, outlying data points, defined as values that differed from the relevant age groups' mean by more than 2 standard deviations (0–2 points per group per condition), were omitted from further consideration in order to focus the analyses on the most typical performance in each age range. All outlying data points were higher than the original group means by 2.2 – 2.8 standard deviations. Therefore, their removal from the child groups diminished any developmental effects in the data set. When compared with the means of the (new) groups that did not include the outliers, the outlying data points were

from 5 – 26 standard deviations higher for FM and from 4 – 11 standard deviations higher for AM. While outlying data points were removed from the statistical analyses reported below, it should be noted that this treatment had no effect on the findings for either AM or FM. The number of participants included in the statistical analyses for each condition and the number of outlying data points excluded from these analyses are shown in Table 1.

3. Results

3.1 AM detection

For all three rates of the AM detection task, average performance but not performance consistency continued to develop beyond 12 years of age. Figure 1 shows the average performance (top row) and performance consistency (bottom row) for the three different AM rates (columns) for the three age groups. There was a significant age effect in a multivariate analysis of variance (ANOVA) with average performance and performance consistency on all three modulation rates as the dependent variables ($F(12,38) = 2.81, p = 0.008$). The multivariate ANOVA was used to account for the correlations among the different dependent variables. Follow up univariate ANOVAs on each AM rate and each index of performance showed that this multivariate effect was due to a significant age effect on average performance for each rate (AM 8: $F(2,23) = 6.58; p = 0.005$; AM 64: $F(2,23) = 8.49; p = 0.002$; AM 125: $F(2,23) = 4.24; p = 0.027$). No significant effects of age were found for performance consistency (all $F(2,23) < 2.00; p \geq 0.158$). Planned comparisons between the adults and the older children showed that average performance on all 3 modulation rates was better for adults ($t > 2.21, p \leq 0.047$), indicating that average performance continued to improve after 12 years of age. There were no significant differences on average performance between the younger and the older children ($t < 1.46, p > 0.15$).

At the individual level, age was related to average performance but not to performance consistency for all 3 modulation rates, in line with the group level findings. Significant or nearly significant correlations between age and average performance were found for all 3 AM rates even when correlations between average performance and performance consistency as well as between age and performance consistency were controlled for by the use of partial correlations (partial correlations between age and average performance: AM 8: $r = -0.35, p = 0.056$; AM 64: $r = -0.60, p = 0.001$; AM 125: $r = -0.52, p = 0.003$). Figure 2 (top row) shows average performance plotted as a function of age for each of the three AM rates (panels), with the values for both average performance and age mathematically adjusted to account for their correlation with performance consistency. Individual listener values were adjusted using the formula $Y_i' = Y_i - B*(X_i - E(X))$. Y' is the adjusted value, Y is the original value, X is the value of the variable being adjusted, $E(X)$ is the mean of that variable, and B is the slope of the X vs. Y regression line. The dashed lines show the linear regression of the adjusted average values and adjusted age. None of the correlations between age and performance consistency (controlling for average performance, Figure 2, bottom row) were significant ($r \leq 0.22; p > 0.23$).

3.2 FM detection

In contrast to the continued development of the average ability to detect AM during adolescence, FM detection was adult-like in terms of both average performance and performance consistency by 8 years of age for all three modulation rates. Figure 3 shows average thresholds (top row) and performance consistency (bottom row) for the three different FM rates (columns) for the three age groups. There was no significant age effect in a multivariate ANOVA ($F(12,30) = 1.63, p = 0.134$), but an inspection of the individual thresholds shown in Figure 3 prompted us to nonetheless carry out follow up univariate

analyses. Consistent with the multivariate analysis, all follow up analyses turned out insignificant (average performance: $F(2,19) < 2.06$; $p > 0.14$; performance consistency defined as standard deviation of reversal values $F(2,19) < 1.78$, $p > 0.19$).

No significant correlations were observed between age and either measure of performance (partial correlations between age and average performance, controlling for consistency: $-0.21 < r < 0.18$, $p > 0.27$; partial correlations between age and performance consistency, controlling for average performance: $-0.25 < r < 0.16$, $p > 0.27$) (see Figure 4). That the results of the analyses conducted on the data of the individual listeners were in full agreement with the age group analyses for both AM and FM detection suggests that the group level findings are not an outcome of the specific age bands used in the current study.

3.3 AM detection vs. FM detection

We compared the overall degrees of immaturity in AM- and FM-detection performance in individual children by computing standardized (Z) AM and FM scores relative to the mean of the adult group for both average performance and performance consistency. Because within each task (AM, FM) there was no statistical evidence for different developmental trajectories across modulation rates, a single Z score was used for each. To obtain the Z scores, we first calculated composite AM and FM scores for each listener and each index of performance by averaging scores (average or consistency) across all 3 modulation rates on each task. Then, to obtain the final Z scores, from each individual score we subtracted the mean adult composite score and divided the resulting difference with the standard deviation of the adult composite score. Larger positive Z scores thus indicate poorer detection or poorer consistency relative to the adult mean. Figure 5 shows scatter plots of the AM and FM Z scores for average performance (top) and performance consistency (bottom) for the younger children (circles), older children (triangles), and adults (squares). The diagonal line in each panel represents equal rates of development for AM and FM, with points below the diagonal representing individuals whose AM performance was less adult-like than their FM performance and points above the diagonal representing the opposite case.

The data shown in Figure 5 confirm, at the individual level, the different developmental trajectories on the two types of modulation detection tasks. For both average performance and performance consistency, there was no significant relationship between the overall degrees of immaturity of AM- and FM-detection performance in individual children. Among the children, the slope of the regression of the FM on the AM Z scores was not significant for either measure (average performance: $\beta = 0.24$, $t = 1.07$, $p = 0.30$; performance consistency: $\beta = 0.04$, $t = 0.15$, $p = 0.87$) (regression lines not shown). Further, for average performance, the spread of the AM scores among the children was wider than that of their FM scores and the points for all but 3 children fell below the diagonal, indicating that AM detection was less adult-like than FM detection for most individual children. For performance consistency, the spread of the children's Z scores was instead wider on FM than on AM detection, with one third of the children less mature on FM than on AM consistency (Figure 5 bottom, data points above the diagonal). The five children with the least consistent FM performance, determined by the Z scores, were inconsistent across all 3 FM rates. However, because these inconsistent FM performers were from both child groups, the group level and individual analyses show no age related changes in FM consistency.

3.4 Potential effects of learning and procedural factors

3.4.1. Learning—The age related effects reported in the previous sections are not likely a result of different learning rates across the three age groups. To investigate whether learning during the testing session contributed to the observed age effects, a separate threshold value for each run of each modulation rate and type (AM or FM) was calculated for each listener

(see Table 2 for average group thresholds and between listener standard deviations for each run). For each of the three AM rates there was a significant main effect of age (3 run $\times$ 3 age repeated-measures ANOVAs: AM 8 Hz: $F = 6.25$, $p = 0.007$; AM 64 Hz: $F = 7.34$, $p = 0.003$; AM 125 Hz: $F = 8.39$, $p = 0.001$), but no significant run (all p values > 0.10) or interaction (all p values > 0.37) effects. For FM detection, for all three rates there were no significant age effects (FM 2 Hz: $F = 3.13$, $p = 0.066$; FM 20: $F = 1.73$, $p = 0.203$; FM 240: $F = 0.71$, $p = 0.51$), nor were there any run (all p values > 0.11) or interaction (all p values > 0.085) effects. Taken together, the outcomes of the individual runs analysis are consistent with the age effects observed when the entire data set was analyzed with no regard to potential learning effects. The one possible exception is for the slowest FM rate, but even here the age and interaction effects failed to reach significance.

It is also worth noting that the range of within-listener performance consistency across runs did not change with age. The threshold difference between the runs with the best and poorest performance did not differ significantly across the three age groups for either AM (multivariate ANOVA: $F = 1.40$, $p = 0.23$) or FM ($F = 1.16$, $p = 0.34$) detection. This outcome is consistent with the lack of development of performance consistency as estimated by the standard deviation of the reversal values (see sections 3.1 and 3.2 above).

3.4.2 Procedural factors—The age related effects observed in the current study also were not likely due to procedural factors related to the ability of children to maintain focus on the task throughout the testing period because two estimates of such factors – performance on easy to detect catch trials and the number of reversals on the adaptive tracks-- did not differ across the age groups. For the catch trials, mean performance ($\pm$ SD) calculated across the three AM conditions was 98 ± 3 , 96 ± 6 and 97 ± 7 percent correct for the adults, older children and younger children respectively ($F = 0.39$, $p = 0.68$). The corresponding values calculated across the three FM rates were 99 ± 3 , 96 ± 7 and 90 ± 15 percent correct ($F = 2.24$, $p = 0.13$). Note that the catch trials were combined across the three modulation rates for each modulation type (AM or FM) due to the small number of such trials per condition. For the number of reversal points on the adaptive tracks, the total did not differ significantly among the three age groups for either the 8-Hz or 125-Hz AM rates ($F \leq 1.06$, $p \geq 0.359$) or for any of the FM rates ($F < 1.7$, $p > 0.2$). The total number did differ significantly across the groups for the 64-Hz AM rate ($F = 6.22$, $p < 0.006$), but this resulted from the older children having fewer reversals than both adults and younger children.

4. Discussion

In the current study we investigated AM and FM detection in school age children and in adults using two indices of performance – average performance and performance consistency. We found that FM detection was adult-like on both measures by 8 years of age, whereas average AM detection continued to improve beyond 12 years of age without corresponding changes in AM performance consistency. Furthermore, within individual children, the degree of immaturity of average detection thresholds as well as of performance consistency were uncorrelated between AM and FM detection. Together, these data suggest that the developmental trajectories for the AM and FM detection tasks used here are at least partially distinct and therefore that different mechanisms may be responsible for the maturation of the ability to detect AM and FM. They further suggest that the development of the ability to detect modulation may develop independently of the ability to perceive it consistently.

Our observation that the ability to detect FM was adult-like by 8 years of age in terms of both average performance and performance consistency is in line with findings from

previous investigations of the development of FM detection (Dawes and Bishop, 2008). Also consistent with those previous results, the one possible exception was the detection of slow (2 Hz) FM, for which a trend towards an age effect was observed in the individual run analysis (section 3.4.1). Interestingly, the present data did not reveal developmental differences between the detection of FM for rates that require reliance on modulation cues (2, 20 Hz) and for a rate that probably involved the use of spectral cues (240 Hz) (e.g., Chen and Zeng, 2004). Therefore, if there are developmental differences between the different FM rates, they must occur earlier than 8 years of age. Because Dawes and Bishop (2008) tested 6–10 year old children and found that, for this age range, the developmental trajectories for 40- and 240-Hz FM detection were similar, studies in preschool children are required to resolve this issue.

The current finding that average AM detection continues to develop during adolescence is in contrast to previous observations that AM detection is adult-like earlier than 12 years of age (Hall and Grose, 1994; Lorenzi et al., 2000). Several stimulus or listener related factors could potentially account for this discrepancy. For example, while we used a 500 ms 8-kHz low-pass carrier, Hall and Grose (1994) used a continuous 200–1200 Hz one. It could be that the use of the wider band or of the non-continuous carrier is responsible for the prolonged trajectories we have observed, although this seems unlikely given that the stimuli used here were similar to those used by Lorenzi et al. (2000), who saw no developmental effects. It is also possible that the children in the current sample had less experience with psychophysical tasks as they had not participated in any previous studies. However, a more probable contributor to the discrepant findings is the difference in sample size. Nearly four times as many 8–12 year old children were tested in the current study ($n = 17–22$) as in the previous investigations (Hall and Grose, 1994, $n = 4$; Lorenzi et al., 2000, $n = 6$). This larger sample size potentially allowed an age effect to become apparent due to greater statistical power. The larger sample size also revealed to a greater extent the variation in detection skills among children. Here, a considerable proportion even of the younger children had thresholds that were within the range of the adults, while the proportion of children with thresholds outside this range decreased with age for all 3 rates, particularly for the faster two. This pattern suggests that the prolonged developmental trajectory we observed resulted because some children were slower to mature than others. It is of interest to note that whereas this is the first demonstration of the development of AM detection during human adolescence, the current findings are consistent with those of a recent study showing that both younger and older juvenile gerbils had significantly higher AM detection thresholds than adult gerbils (Sarro and Sanes, 2010).

The developmental changes observed here on AM detection do not appear to have arisen from the maturation of general non-sensory functions. We define non-sensory functions as those that influence performance across conditions in a similar manner, such as being able to understand the response demands, to comply with the requirements of the adaptive psychophysical procedure, or to attend to the task over a range of difficulty levels. As mentioned in the Introduction, there are several reports in which average performance and performance consistency on auditory skills appeared to mature in parallel (Allen et al., 1989; Moore et al., 2008; Wightman et al., 1989). In those reports performance consistency (assessed as either the range or standard deviation of reversals in a single run or as the threshold range across runs) was assumed to reflect non-sensory factors and therefore the parallel development of this measure and average performance in school-age children was interpreted as arising primarily from non-sensory functions (Allen et al., 1989, Wightman et al., 1989, Moore et al., 2008). The current finding that performance consistency (estimated in two different ways) reached the adult level prior to average performance on all 3 AM rates is inconsistent with this account. We did not see a similar developmental dissociation between average performance and performance consistency for the detection of FM,

potentially because both measures were already adult-like in the youngest child group we tested (8–10 year olds). However, such a dissociation was observed in a previous study of the development of FM detection that included 6–10 year old children (Dawes and Bishop 2008), as well as in an investigation of the development of frequency discrimination in which adolescents with non-adult-like performance were as consistent as those with adult-like performance (Banai, 2008). Another indication that the prolonged development of AM detection may not have arisen from the maturation of non-sensory functions comes from the present analysis of the catch trials – the 10% of trials that were designed to determine whether listeners were attending to the task. To the extent that catch trials are a reasonable measure of that ability, the finding that the response to catch trials did not change with age for AM or FM detection, and that the level of performance on those trials did not differ between the tasks, suggests that development of this attentional process likely did not contribute to the more prolonged maturation of AM than FM detection.

The present results instead may reflect, at least in part, maturation of sensory processing, defined here as processing at any point along the auditory pathway that is unique to a specific condition or stimulus and that is thus not shared between AM and FM detection. Findings that intensity discrimination matures earlier than frequency discrimination (Jensen and Neff, 1993) and that backward masking reaches the adult level later than simultaneous (Hartley et al., 2000) or forward (Wright and Zecker, 2004) masking, even when assessed in a within listener design and with similar methodology, suggest that development can derive from the maturation of sensory processes. The distinct developmental trajectories observed here for AM and FM detection fit with this possibility. They are also consistent with other indications that AM and FM are processed by mechanisms that are at least somewhat distinct (Moore and Sek, 1994; Moore and Sek, 1995; Regan and Tansley, 1979; Tansley and Suffield, 1983). For instance, it has been reported that repeated presentation of either AM or FM sounds results in adaptation that is specific to the type of modulation presented during the adaptation phase (Regan and Tansley, 1979; Tansley and Suffield, 1983). Further, while it has been suggested that AM and FM are encoded by a common neural response (e.g., Saberi and Hafter, 1995), at least some components of the neural circuitry have been found to respond differentially to AM and FM signals (Dimitrijevic et al., 2001; Hart et al., 2003). Thus, the present results may indicate either that neural circuitry that is more specialized for AM matures later than that specialized for FM or that a common neural circuitry is more sensitive to FM than to AM, resulting in more adult-like FM than AM detection in children.

An alternative sensory interpretation that we find less likely is that the developmental differences arose due to the use of different carriers for AM (noise carriers) and FM (pure tone carriers) detection. This interpretation is in line with the idea that higher areas along the auditory pathway play a greater role in the processing of wideband stimuli than lower areas (Nelken, 2008), because higher areas are known to develop later than lower areas. However, it is not consistent with previous behavioral investigations of development showing that the processing of wideband stimuli does not necessarily reach adult level later than that of narrow-band stimuli. For example, whereas comodulation masking release, taken as a measure of across channel processing was mature by 6 years of age, temporal resolution, used as a measure of within channel processing was not fully adult-like by 10 years of age (Grose et al., 1993). Furthermore, pure tone frequency discrimination was not mature by 10 (Moore et al., 2008) or even 12 (Banai and Ahissar, 2006) years of age, and the responses of the human auditory cortex to pure tones continued to develop during adolescence (Sussman et al., 2008). Finally, given that we selected stimuli that we assumed would yield near-optimal performance in adults, at the very least, these data suggest that the age at which such performance is reached differs between AM and FM detection.

Another possibility is that the more prolonged development of AM than FM detection reflects the maturation of a process that responds differently to different acoustic parameters, but that serves neither a purely sensory nor a purely non-sensory function. One such process, which has been suggested to have a prolonged developmental trajectory (Gomes et al., 1999; Keller and Cowan, 1994), is short-term memory for sensory events. Such sensory memory, which spans the time scale of seconds (to possibly minutes) is required to perform multi-interval tasks. If the sensory memory of younger children is faster to decay than that of older children and adults, this developmental change could account for maturational improvements in perceptual skills that rely on this memory. Furthermore, in adults the duration of sensory memory appears to differ for different auditory cues. For instance, memory for the intensity of pure tones is faster to decay than memory for pitch (Clement et al., 1999). It is thus possible that AM detection takes longer to mature because memory for AM in children decays faster than that for FM. These observed and posited characteristics imply that there may be a task-specific memory that is an emergent feature of the sensory system itself rather than an outcome of a general memory/non-sensory process. This idea receives support from evidence that the same sensory areas are involved in encoding and remembering the sensory signal (for a review see Pasternak and Greenlee, 2005). For example, imaging studies within the same individuals have shown that memory traces for linguistic materials are represented in auditory areas for spoken language, but in visual areas for sign language (Pa et al., 2008; Ronnberg et al., 2004).

Finally, the present observation that auditory development of average performance on AM detection continued into adolescence connects these data with those from the small group of other studies showing development in the performance of (Banai, 2008; Halliday et al., 2008; Hartley et al., 2000; Maxton and Hochberg, 1982; Moore et al., 2008; Wightman et al., 2010), or learning on (Huyck and Wright, 2011) auditory psychophysical tasks after 10 years of age. It is also in line with findings showing that in humans the auditory cortex itself continues to develop well into the teenage years (e.g., Moore and Linthicum, 2007; Sussman et al., 2008). Combined with the different maturational courses that have been documented for different auditory tasks, these findings suggest that sensory related functions may have prolonged maturational trajectories, similar to those of other cognitive functions. Therefore theories of human development that focus on cognitive maturation beyond early childhood may benefit from considering perceptual development as well.

Research highlights

1. Maturation of amplitude modulation (AM) and frequency modulation (FM) detection was compared.
2. Average detection ability matured later for AM (>12 years of age) than for FM (<8 years of age).
3. Performance consistency matured <8 years of age for both AM and FM detection.
4. Results are more consistent with sensory than with attentional development.

Abbreviations

AM	amplitude modulation
FM	frequency modulation
ANOVA	analysis of variance

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References

- Allen P, Wightman F, Kistler D, Dolan T. Frequency resolution in children. *J. Speech. Hear. Res.* 1989; 32:317–322. [PubMed: 2739383]
- Banai K. Auditory frequency discrimination development depends on the assessment procedure. *J. Basic. Clin. Physiol. Pharmacol.* 2008; 19:209–222. [PubMed: 19025032]
- Banai K, Ahissar M. Auditory processing deficits in dyslexia: task or stimulus related? *Cereb. Cortex.* 2006; 16:1718–1728. [PubMed: 16407480]
- Boets B, Wouters J, van Wieringen A, Ghesquiere P. Auditory temporal information processing in preschool children at family risk for dyslexia: relations with phonological abilities and developing literacy skills. *Brain. Lang.* 2006; 97:64–79. [PubMed: 16112723]
- Chen H, Zeng FG. Frequency modulation detection in cochlear implant subjects. *J. Acoust. Soc. Am.* 2004; 116:2269–2277. [PubMed: 15532658]
- Clement S, Demany L, Semal C. Memory for pitch versus memory for loudness. *J. Acoust. Soc. Am.* 1999; 106:2805–2811. [PubMed: 10573896]
- Dawes P, Bishop DV. Maturation of visual and auditory temporal processing in school-aged children. *J. Speech. Lang. Hear. Res.* 2008; 51:1002–1015. [PubMed: 18658067]
- Dimitrijevic A, John MS, van Roon P, Picton TW. Human auditory steady-state responses to tones independently modulated in both frequency and amplitude. *Ear. Hear.* 2001; 22:100–111. [PubMed: 11324839]
- Gomes H, Sussman E, Ritter W, Kurtzberg D, Cowan N, Vaughan HG. Electrophysiological evidence of developmental changes in the duration of auditory sensory memory. *Dev. Psychol.* 1999; 35:294–302. [PubMed: 9923483]
- Groose JH, Hall JW 3rd, Gibbs C. Temporal analysis in children. *J. Speech. Hear. Res.* 1993; 36:351–356. [PubMed: 8487526]
- Hall JW 3rd, Grose JH. Development of temporal resolution in children as measured by the temporal modulation transfer function. *J. Acoust. Soc. Am.* 1994; 96:150–154. [PubMed: 7598757]
- Halliday LF, Taylor JL, Edmondson-Jones AM, Moore DR. Frequency discrimination learning in children. *J. Acoust. Soc. Am.* 2008; 123:4393–4402. [PubMed: 18537390]
- Hart HC, Palmer AR, Hall DA. Amplitude and frequency-modulated stimuli activate common regions of human auditory cortex. *Cereb. Cortex.* 2003; 13:773–781. [PubMed: 12816893]
- Hartley DE, Wright BA, Hogan SC, Moore DR. Age-related improvements in auditory backward and simultaneous masking in 6- to 10-year-old children. *J. Speech. Lang. Hear. Res.* 2000; 43:1402–1415. [PubMed: 11193961]
- Huyck JJ, Wright BA. Late maturation of auditory perceptual learning. *Dev. Sci.* 2011; 13:614–621. [PubMed: 21477199]
- Jensen JK, Neff DL. Development of Basic Auditory-Discrimination in Preschool-Children. *Psycho. Sci.* 1993; 4:104–107.
- Keller TA, Cowan N. Developmental Increase in the Duration of Memory for Tone Pitch. *Dev. Psychol.* 1994; 30:855–863.
- Lorenzi C, Dumont A, Fullgrabe C. Use of temporal envelope cues by children with developmental dyslexia. *J. Speech. Lang. Hear. Res.* 2000; 43:1367–1379. [PubMed: 11193958]
- Maxton AB, Hochberg I. Development of Psychoacoustic Behavior: Sensitivity and Discrimination. *Ear. Hear.* 1982; 3:301–308. [PubMed: 7152153]
- Moore BC, Sek A. Discrimination of modulation type (amplitude modulation or frequency modulation) with and without background noise. *J. Acoust. Soc. Am.* 1994; 96:726–732. [PubMed: 7930073]

- Moore BC, Sek A. Effects of carrier frequency, modulation rate, and modulation waveform on the detection of modulation and the discrimination of modulation type (amplitude modulation versus frequency modulation). *J. Acoust. Soc. Am.* 1995; 97:2468–2478. [PubMed: 7714263]
- Moore DR, Ferguson MA, Halliday LF, Riley A. Frequency discrimination in children: perception, learning and attention. *Hear. Res.* 2008; 238:147–154. [PubMed: 18222053]
- Moore JK, Linthicum FH Jr. The human auditory system: a timeline of development. *Int. J. Audiol.* 2007; 46:460–478. [PubMed: 17828663]
- Nelken I. Processing of complex sounds in the auditory system. *Curr. Opin. Neurobiol.* 2008; 18:413–417. [PubMed: 18805485]
- Pa J, Wilson SM, Pickell H, Bellugi U, Hickok G. Neural organization of linguistic short-term memory is sensory modality-dependent: evidence from signed and spoken language. *J. Cogn. Neurosci.* 2008; 20:2198–2210. [PubMed: 18457510]
- Pasternak T, Greenlee MW. Working memory in primate sensory systems. *Nat. Rev. Neurosci.* 2005; 6:97–107. [PubMed: 15654324]
- Regan D, Tansley BW. Selective adaptation to frequency-modulated tones: evidence for an information-processing channel selectively sensitive to frequency changes. *J. Acoust. Soc. Am.* 1979; 65:1249–1257. [PubMed: 458046]
- Ronnberg J, Rudner M, Ingvar M. Neural correlates of working memory for sign language. *Brain. Res. Cogn. Brain. Res.* 2004; 20:165–182. [PubMed: 15183389]
- Saberi K, Hafter ER. A common neural code for frequency- and amplitude-modulated sounds. *Nature.* 1995; 374:537–539. [PubMed: 7700378]
- Sarro EC, Sanes DH. Prolonged maturation of auditory perception and learning in gerbils. *Dev. Neurobiol.* 2010; 70:636–648. [PubMed: 20506133]
- Shannon RV, Zeng FG, Kamath V, Wygonski J, Ekelid M. Speech recognition with primarily temporal cues. *Science.* 1995; 270:303–304. [PubMed: 7569981]
- Stickney GS, Nie K, Zeng FG. Contribution of frequency modulation to speech recognition in noise. *J. Acoust. Soc. Am.* 2005; 118:2412–2420. [PubMed: 16266163]
- Sussman E, Stemschneider M, Gumenyuk V, Grushko J, Lawson K. The maturation of human evoked brain potentials to sounds presented at different stimulus rates. *Hear. Res.* 2008; 236:61–79. [PubMed: 18207681]
- Sutcliffe P, Bishop D. Psychophysical design influences frequency discrimination performance in young children. *J Exp Child Psychol.* 2005; 91:249–270. [PubMed: 15890352]
- Talcott JB, Witton C, McLean MF, Hansen PC, Rees A, Green GG, Stein JF. Dynamic sensory sensitivity and children's word decoding skills. *Proc. Natl. Acad. Sci. USA.* 2000; 97:2952–2957. [PubMed: 10688885]
- Tansley BW, Suffield JB. Time course of adaptation and recovery of channels selectively sensitive to frequency and amplitude modulation. *J. Acoust. Soc. Am.* 1983; 74:765–775. [PubMed: 6630734]
- Wightman F, Allen P, Dolan T, Kistler D, Jamieson D. Temporal resolution in children. *Child. Dev.* 1989; 60:611–624. [PubMed: 2737011]
- Wightman FL, Kistler DJ, O'Bryan A. Individual differences and age effects in a dichotic informational masking paradigm. *J. Acoust. Soc. Am.* 2010; 128:270–279. [PubMed: 20649222]
- Wright BA, Zecker SG. Learning problems, delayed development, and puberty. *Proc. Natl. Acad. Sci. USA.* 2004; 101:9942–9946. [PubMed: 15210987]
- Zeng FG, Nie K, Stickney GS, Kong YY, Vongphoe M, Bhargave A, Wei C, Cao K. Speech recognition with amplitude and frequency modulations. *Proc. Natl. Acad. Sci. USA.* 2005; 102:2293–2298. [PubMed: 15677723]

Figure 1.

AM detection performance for different age groups. Top row: average performance, expressed as the modulation depth (%) required for 79.4% correct detections, as determined from the mean of all reversal values in the final data set for each listener. Bottom row: performance consistency, defined as the standard deviation of the reversal values included in the average. Filled symbols represent group means; empty symbols represent individual listeners' data; error bars show ± 1 standard error of the mean (sem). The different modulation rates are shown in separate columns (left to right: 8, 64, 125 Hz).

Figure 2.

AM average performance (top) and performance consistency (bottom) as a function of age. Symbols represent individual listener values – circles for 8–10 year olds, triangles for 11–12 year olds and squares for adults. The values were mathematically adjusted for both average performance and age to account for their correlation with performance consistency (top), or for both performance consistency and age to account for their correlation with average performance (bottom) (see text). The dashed lines show the linear regression of the adjusted average/consistency values and adjusted age. The different modulation rates are shown in separate columns (left to right: 8, 64, 125 Hz).

Figure 3.

FM detection performance for different age groups. Top row: average performance. Bottom row: performance consistency. The different modulation rates are shown in separate columns (left to right: 2, 20, 240 Hz). See caption to Figure 1 for details. Values higher than 2.5 % are denoted with arrow marks, with the actual values noted by the arrow.

Figure 4. FM average performance (top) and performance consistency (bottom) as a function of age. The different modulation rates are shown in separate columns (left to right: 2, 20, 240 Hz). See caption to Figure 2 for details.

Figure 5.

FM vs. AM Z scores. Top. Average performance. Bottom. Performance consistency. Z scores were calculated relative to mean adult performance with larger values denoting less mature performance. The diagonal line on each panel represents equal development for AM and FM. Points below the diagonal represent less adult-like performance on AM relative to FM. 8–10 year old children are depicted with circles, 10–12 year olds with triangles and adults with shaded squares.

Table 1
Number of listeners included in the statistical analysis by condition and age

Numbers in parentheses are the number of outlying data points excluded from the analysis for each condition.

Condition	Younger children (8–10 y/o)	Older children (11–12 y/o)	Adults
AM 8 Hz	9 (1)	9 (1)	11
AM 64 Hz	10 (1)	9 (1)	11
AM 125 Hz	12	10 (1)	10 (1)
FM 2 Hz	10 (1)	10 (1)	9
FM 20 Hz	10	10	9 (1)
FM 240 Hz	8 (1)	9 (1)	6 (1)

Table 2
Average group detection thresholds (top row in each cell) and between listener standard deviations (bottom row in each cell) by run

A. AM detection (% modulation)												
Age Group												
8–10 y/o				11–12 y/o				adults				
Run				Run				Run				
Modulation rate	1	2	3	1	2	3	1	2	3	1	2	3
8 Hz	23.9 4	29.0 9	31.1 11	30.2 6	34.0 15	27.9 14	22.4 7	20.6 5	20.2 5			
64 Hz	38.4 15	42.5 18	49.9 22	30.1 6	34.9 7	32.8 11	24.9 11	23.0 7	29.1 11			
125 Hz	36.5 10	40.3 14	46.0 17	34.4 11	38.3 20	34.6 8	26.6 7	26.2 9	23.4 8			

B. FM detection (% modulation)												
Age Group												
8–10 y/o				11–12 y/o				adults				
Run				Run				Run				
Modulation rate	1	2	3	1	2	3	1	2	3	1	2	3
2 Hz	1.96 2.7	0.96 0.9	0.85 0.9	0.39 0.2	0.36 0.1	0.62 0.6	0.33 0.1	0.27 0.1	0.28 0.1			
20 Hz	0.50 0.2	1.37 1.8	1.57 1.5	0.62 0.3	1.09 1.1	0.53 0.2	0.75 0.8	0.47 0.2	0.41 0.2			
240 Hz	1.91 1.8	4.03 5.3	3.99 3.3	0.47 0.40	0.81 0.9	0.57 0.7	4.68 9.9	6.67 15	0.74 0.4			

Threshold values are based on data from all listeners (see Table 1) except for the 240 Hz FM condition in which two 11–12 y/o and five 8–10 y/o children had insufficient reversals (< 4) to calculate a threshold on at least one of the runs and were thus removed from this analysis.