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PII: S0378-5955(21)00237-9
DOI: https://doi.org/10.1016/j.heares.2021.108403
Reference: HEARES 108403

To appear in: *Hearing Research*

Received date: 27 June 2021
Revised date: 17 November 2021
Accepted date: 25 November 2021

Please cite this article as: Laurianne Cabrera , Irene Lorenzini , Stuart Rosen , Léo Varnet , Christian Lorenzi , Temporal integration for amplitude modulation in childhood: Interaction between internal noise and memory, *Hearing Research* (2021), doi: https://doi.org/10.1016/j.heares.2021.108403

Temporal integration for amplitude modulation in childhood: Interaction between internal noise and memory

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Highlights:

- With increasing number of AM cycles, children and adults exhibit better AM detection thresholds
- 5-to 6-year-olds displayed worse thresholds with 2 AM cycles than other age groups
- Young adults showed better thresholds with 8 AM cycles than other age groups

Changes in internal noise combined with memory capacities simulated those differences
Thus, late processing stages for AM continue to develop late into childhood

Abstract

It is still unclear whether the gradual improvement in amplitude-modulation (AM) sensitivity typically found in children up to 10 years of age reflects an improvement in "processing efficiency" (the central ability to use information extracted by sensory mechanisms). This hypothesis was tested by evaluating temporal integration for AM, a capacity relying on memory and decision factors. This was achieved by measuring the effect of increasing the number of AM cycles (2 vs 8) on AM-detection thresholds for three groups of children aged from 5 to 11 years and a group of young adults. AM-detection thresholds were measured using a forced-choice procedure and sinusoidal AM (4 or 32 Hz rate) applied to a 1024-Hz pure-tone carrier. All age groups demonstrated temporal integration for AM at both rates; that is, significant improvements in AM sensitivity with a higher number of AM cycles. However, an effect of age is observed as both 5-6 year olds and adults exhibited more temporal integration compared to 7-8 and 10-11 year olds at both rates. This difference is due to: (i) the 5-6 year olds displaying the worst thresholds with 2 AM cycles, but similar thresholds with 8 cycles compared to the 7-8 and 10-11 year olds, and, (ii) adults showing the best thresholds with 8 AM cycles but similar thresholds with 2 cycles compared to the 7-8 and 10-11 year olds. Computational modelling indicated that higher levels of internal noise combined with poorer short-term memory capacities in children accounted for the developmental trends. Improvement in processing efficiency may therefore account for the development of AM detection in childhood.

Keywords Childhood, amplitude modulation, temporal integration, internal noise, short-term memory.

INTRODUCTION

Amplitude-modulation (AM) information represents the slow temporal variations in amplitude over time of incoming sounds. AM is essential for speech comprehension as slow modulations (< 5-8 Hz) convey important linguistic information (Drullman et al., 1994a, 1994b; Rosen, 1992; Varnet et al., 2017). To date, only a few studies have assessed in children the development of the ability to detect and discriminate slow AM fluctuations. Nevertheless, a typical development of slow AM perception is likely to be a pre-requisite of typical auditory and linguistic development (Goswami et al., 2002; Lorenzi et al., 2000; Witton et al., 2002).

Improvement in AM detection sensitivity during childhood may reflect the maturation of sensory-processing mechanisms leading to better temporal resolution with age, implying a better ability to follow fast changes in AM over time. Conversely, it is also possible that such improvement could reflect development in “processing efficiency”. This would posit that the temporal resolution of the auditory system is adult-like but the ability to make optimal use of the extracted sensory information is not. This latter hypothesis was suggested in a pioneering study by Hall and Grose (1994). They showed that auditory sensitivity to sinusoidal AM, as measured by detection thresholds, improves with age between 5 and 10 years, but that AM sensitivity was similarly affected by AM rate (ranging from 5 to 200 Hz) at all ages. This suggests that sensory factors constraining temporal resolution are mature early on, as also suggested by studies with young infants (Walker et al., 2019). However, in a recent similar study, Buss et al. (2019) found evidence that temporal resolution may be poorer in children than in adults for low AM rates. In this study, 5-to-11-year-old children and adults had to detect a target sinusoidal AM applied to a 4300-Hz pure-tone carrier at three AM rates: 16, 64, and 256 Hz. The results replicated improvement in AM detection thresholds with age at higher AM rates, 64 and 256 Hz, but this was less clear for the slower rate of 16 Hz. In another study, Peter et al. (2014) assessed AM detection thresholds in 8 to 11 year olds, 12- to 17 year olds and young adults using broadband noise carriers and AM rates ranging from 4 to 128 Hz. Although, they did not observe a significant interaction between age and modulation frequency, they observed slightly worse thresholds in 8- to 11-year-old children compared to older children for a 4 Hz modulation rate, but not at higher AM rates.

Note though that Hall and Grose (1994), Peter et al., (2014) and Walker et al. (2019) used a stochastic (broadband noise) carrier whereas Buss et al. (2019) used a deterministic one (a pure tone). It is thus possible that the external variability in acoustic stimuli may influence AM detection thresholds in childhood, and that temporal resolution even at low rates might improve between 5 and 11 years.

Another way to assess the development of sensory-processing mechanisms is to explore susceptibility to AM masking. It is now commonly assumed that AM perception reflects the operation of a bank of modulation filters selectively tuned for AM rate (Biberger and Ewert, 2016; Dau et al., 1997a) that are implemented centrally in the auditory system (Liégeois-Chauvel et al., 2004). ñAM maskingò effects are observed in psychophysical tasks using either two simultaneous sounds, a target and a masker, that fluctuate at a similar AM rate, or when the target and masking AM are simultaneously presented and applied to the same carrier. In such tasks, an elevation of detection thresholds for the target AM is observed, reflecting the selectivity of modulation filters for AM rate (Bacon and Grantham, 1989; Houtgast, 1989).

In an additional experiment, Buss et al. (2019) measured AM masking in children and adults. The results showed comparable effects of masker AM rate and a lack of interaction with age suggesting that modulation selectivity is mature by 5 years of age. Nevertheless, the overall effect of age on detection thresholds in the masked conditions indicates reduced efficiency in AM processing in childhood. Cabrera et al. (2019) explored further the development of AM masking in childhood and the role of ñprocessing efficiencyò (in the case of AM perception, the ability to make optimal use of the available temporal-modulation information at the output of modulation filters). It was hypothesized that poor AM detection thresholds in childhood may relate to higher levels of internal noise (neural variability at each level of the auditory system) and/or the use of sub-optimal decision strategies. In this study, detection thresholds were measured for slow sinusoidal AM (with a rate of 4, 8, or 32 Hz) applied to carriers whose inherent random modulations exerted different amounts of AM masking. More specifically three carriers were used: a pure tone, a narrowband noise with small inherent random AM fluctuations and a narrowband noise with higher inherent random AM fluctuations. Results showed that between 5 and 11 years, AM detection thresholds improved and surprisingly, that susceptibility to AM masking caused by the inherent random AM fluctuations of the narrowband noise carriers increased with age. Computer simulations of an auditory model based on the modulation-filterbank concept was used to simulate 1) poor sensory processing by changing the degree of selectivity of modulation filters; 2) poor processing efficiency by varying levels of internal noise at the output of the modulation filters; or 3) poor processing efficiency by simulating a suboptimal decision strategy. The model reducing internal noise levels with age by a factor 10 better accounted for the observed developmental trends between 5 and 11 years. Altogether, the findings on AM masking suggest that at least some aspects of AM processing mature during childhood.

To explore further the development of processing efficiency for AM in childhood, the current study focused on a phenomenon known as ñtemporal integrationò for AM cues. Several studies in adults have shown that AM detection improves with an increasing number of AM cycles (Dau et al., 1997b; Sheft and Yost, 1990; Viemeister, 1979; Wallaert et al., 2018, 2017, 2016). This so-called ñtemporal integrationò is currently assumed to reflect high-level, i.e., central, decision processes involving ñmultiple looksò (Viemeister and Wakefield, 1991) or a template-matching process (Dau et al., 1997b). Consistent with this idea, electrophysiological work conducted on gerbils showed that the parietal cortex is required to temporally integrate AM information, and thus, accumulate sensory evidence for discrimination decisions. Yao et al. (2020) measured gerbilsô discrimination abilities between 4 and 10 Hz AM modulated noises using a behavioural task. The stimulus duration varied from 100 to 2000 ms to assess the shortest stimulus duration for which animals could discriminate AM, reflecting integration time. Pharmacological inactivation of the parietal cortex was shown to increase minimum integration times. More specifically, when the excitatory projections from auditory cortex to parietal cortex were chemogenetically inactivated, the behavioural integration time was significantly reduced, showing the role of parietal cortex in temporal integration of AM cues.

A recent investigation of temporal integration conducted with adult human listeners combining a psychophysical and modelling approach indicates that for low AM rates (below 5 Hz), temporal integration is also constrained by the limited capacity of short-term auditory memory (Wallaert et al., 2017, 2018). In these studies, AM detection thresholds are measured in adult listeners as a function of the number of AM cycles available in the stimuli. A computational model was used to simulate the thresholds implementing different sources of internal noise supposed to limit the performance when processing AM. An additive noise was introduced to limit intensity discrimination and AM sensitivity. An additive time-varying memory noise was introduced to simulate imperfect retention of temporal-envelope information in each observation interval. All internal noises were modeled as Gaussian noises, and added independently to the output of the bandpass AM filter in the model.

In children, previous studies used only fixed stimulus durations to assess the effect of different AM rates on detection thresholds. Peter et al. (2014) suggested that the slightly worse thresholds observed at low AM rates may relate to the low number of cycles available in the target signal when the stimulus duration is kept constant at 500 ms. In their study, the 4-Hz rate involved the lowest number of AM cycles, 2 cycles, compared to the other AM rates tested. In contrast, Lorenzi et al. (2000) varied the target-stimulus duration from 500 to 1500 ms for a 4 Hz modulation rate and observed similar temporal integration between adults and six children between 8 and 15 years, suggesting no improvement between childhood and adulthood.

The present study sought to measure temporal integration at two different AM rates in a large cohort of children aged between 5 and 11 years, in order to probe the integrity and maturation of memory and decision processes in the AM domain. The main goal of the present study was to: 1) evaluate the effect of increasing the number of AM cycles (2 vs 8 cycles) on detection thresholds between 5 and 11 years for two slow AM rates (4 and 32 Hz) and, 2) use computational modelling to test whether AM-detection data in children were better simulated by changes in the characteristics of

AM filtering, internal noise and/or short-term memory capacities. It was assumed that temporal integration for AM detection should reflect the operation of the late, decision stage of AM processing (Dau et al., 1997b). It was also assumed that at the lower AM rate (4 Hz) where stimuli are longer in duration, temporal integration should reflect the additional constraints imposed by the limited echoic memory buffer involved in AM processing (King et al., 2019; Wallaert et al., 2018, 2017). If all age groups are similarly affected by the number of AM cycles or by AM rates, this would indicate that temporal integration is developed by 5 years and that central aspects of processing efficiency related to short-term memory and decision making for AM processing are well developed in childhood. However, if younger and older children are affected differently by the number of AM cycles and by AM rates, this would suggest that memory and decision mechanisms are still evolving and thus, that processing efficiency for AM continues to develop into childhood.

METHODS

Participants

Seventy-two children and 30 adults were included in this experiment (see also Cabrera et al., 2019). All participants reported typical cognitive development. Consent was obtained from parents and adult participants as approved by the university ethics committee. Adult participants received a monetary compensation for their time and children collected stickers on a science certificate to keep them motivated.

For both children and adults, absolute thresholds were assessed for both ears at octave frequencies between 0.25 and 8 kHz prior to testing. Two participants (one child and one adult) were excluded because their absolute thresholds for pure tones were above the normal range (>20 dB HL).

An additional 9 children were tested but not included in the final sample: three were at floor levels of performance for more than the half of the conditions (all aged 5-6 years), one withdrew from the study, four were not at school during testing, and one was excluded because of experimental error. Four adults were not included in the final sample because of missing data due to experimental errors. Furthermore, an outlier labelling rule (Hoaglin and Iglewicz, 1987) was applied to the data set. A total of 10 outliers were flagged and their data were not included in the analyses (see Cabrera et al., 2019). Four outliers were flagged in the 5ï 6 year-old group, two in the 7ï 8 year olds, four in the 10ï 11 year olds, and two in the adult group (11% of the data). When those outliers were removed, the data did not differ from normality (Kolmogorov-Smirnov test, all ps > 0.05).

The final sample included: 21 5-6-year-olds (10 females; mean age = 5.7 years, SD = 0.4), 27 7-8-year-olds (13 females; mean age = 7.8 years, SD = 0.5), 24 10-11-year-olds (12 females; mean age = 10.7, SD = 0.4) and 30 adults (22 females, mean age = 22.5 years, SD = 2.5).

Stimuli

A full factorial design led to four experimental conditions: two target AM rates (f_m: 4 and 32 Hz) presented for two numbers of modulation cycles (2 and 8). As previous studies showed that optimal AM detection is observed with 4-5 cycles, we selected 8 cycles to ensure that listeners are presented with a sufficient number of cycles (Edwards et al., 2008; Lee and Bacon, 1997). In all conditions, the stimuli included 50-ms raised-cosine onset/offset ramps, and the inter-stimulus interval was 500 ms. Standard sounds were not modulated in amplitude, and target sounds were modulated at depths ranging from m = 100% to m =1 %, in 20 steps of 2 dB. The starting phase

specific result, unrelated to sound duration, may relate to *inefficiencies in processing the temporal-envelope information when few cycles are available*.

To explore further the stages of AM processing that may develop over age, we used a computational model based on the modulation-filter bank concept simulating peripheral and central constraints in AM processing. The results of the modelling study reveal that, contrary to a previous study on AM masking (Cabrera et al., 2019), the observed data are not well simulated by a simple decrease in the level of internal noise over age: A progressive decrease in the level of internal noise during childhood predicts better temporal integration with increasing age while the real data show better temporal integration in the youngest group (5-6 years). Additional simulations indicate that changes in short-term adaptation cannot account for the change in temporal integration over age; changing the weight of transients does not influence the model's predictions for 5-6-years or adults, nor does it improve the model's predictions for the other two child groups. Changing the characteristics of adaptation provides a slightly better fit for the 2-cycles condition at 7-8 years but this improvement is not sufficiently large. Thus, children do not seem to weight differently transient responses over age.

Finally, the only aspect of AM processing changing over age that yields better predictions for the 7-8 and 10-11 year groups is imperfect retention of temporal-envelope information, as proposed by Wallaert et al. (2017). In the present model, this constraint is simulated by degrading the temporal-envelopes of incoming signals at the output of modulation filters with an additive, exponential memory noise. Temporal-envelope cues are more masked by memory noise near the onset of the stimulus. Increasing the SD of the memory noise lengthens the initial portion of the stimulus that is most impacted by the memory noise, reducing by the same amount the length of the final portion that makes an effective contribution to decision making. The imperfect retention of temporal-envelope information in each observation interval necessarily has a greater detrimental effect on the detection of the longest stimuli, e.g., at 8 AM cycles. The fact that increasing memory noise only improves model predictions for the 7-8 years and 10-11 years suggests that: 1) The level of the additive internal noise at 5-6 years is high enough to dominate any effect of memory noise; 2) the level of the memory noise decreases over age, as adults showed significantly better thresholds than the child groups in the 8-cycle condition; 3) AM processing is still not fully mature in late childhood, but this may relate to inefficiency at higher levels of processing, i.e., echoic memory.

Echoic memory, or "auditory sensory memory", is the ability to retain a sound stimulus right after its occurrence, allowing further processing. This type of memory is described as a pre-attentive phase of 100-300 ms where auditory information is temporarily stored for further manipulation (Cowan, 1984; Massaro, 1972). So far, developmental studies have shown that this cognitive function improves throughout childhood and reaches its peak in early adulthood. Evoked-potential investigations have tested the short-term retention and processing of tones, in children *vs* adults, through oddball paradigms assessing the Mismatch Negativity (MMN) to deviant tones differing in frequency or duration. These studies have globally revealed reduced amplitude and higher latency of the MMN up to 10 years of age, which is thought to reflect the shorter duration and faster decay of the sensory memory trace (see Bartha-Doering et al., 2015 for a review). Keller and Cowan (1994) reported comparable results from a 2I-2AFC tone-comparison task, and concluded that the persistence of echoic memory for tones is shorter in children of 6-to-7-year-olds than adults. The clear-cut differences in echoic memory performance between children and adults may explain why the model predictions for AM detection are improved by simulating imperfect retention of temporal-envelope information in childhood.

The dynamics behind the protracted improvement of echoic memory are not yet clear. It has been proposed that a general increase in global processing speed might mediate this process (Ferguson and Bowey, 2005). Neural maturation of specific brain areas may also play a role in improvement of echoic memory. Recent neurophysiological studies in animals suggest that parietal cortex activity relates to the integration of AM information (Yao et al., 2020). When excitatory auditory cortex inputs to parietal cortex are inhibited, this results in reduced temporal integration in gerbils for AM-target stimulations of 100, 300 and 600 ms. When parietal cortex is directly deactivated, increased errors at long stimulus durations, of 1 or 2 sec, are observed, suggesting that the parietal cortex integrates sensory input from the primary auditory cortex and thus, plays an essential role in an auditory decision task.

Whether parietal cortex is more specifically involved in information retention is still under investigation. Lesion studies suggest that parietal areas are involved in memory judgments through decision making. For instance, patients with parietal lesions show more difficulties in integrating new external cues with internal memory evidence (Dobbins et al., 2012). Finally, the role of prefrontal areas in decision making (Hanks et al., 2015), as well as of auditory areas in auditory short term memory (Scott et al., 2014) need to be specified in such temporal integration tasks. Better knowledge of the specific development of those cortical regions and their implications for AM processing would help to better understand what stages of processing are still developing through childhood. Computational modelling may also help in future studies to simulate the development of memory processing and of decision making in AM detection.

It is worth noting that our current model did not take into account the potential detrimental effects of memory capacities on the whole sequence of stimuli composing a given trial in the 3AFC procedure. Memory limitations may have not only affected the internal representation (and especially the onset) of each stimulus, but also the whole sequence of stimuli composing a given trial. This may especially be the case when using 8 cycles at 4 Hz, where the whole trial lasts for 7 s. In other words, the internal representation of the first stimulus of a given trial might have been more affected by memory limitations than the internal representation of the second or last stimulus. The current modelling architecture aimed to reproduce aspects of echoic memory in the AM domain, not such effects over the whole trial. For 7-s long sequences of sounds, other aspects of memory may come into play such as working memory. Further work is warranted to investigate such constraints in temporal envelope retention. Still, using a 3AFC procedure, where the position of the target trial is randomized on each trial, this effect should be averaged out in the results. It is also noteworthy that the current model succeeded in reproducing the 4-Hz data without taking account of the temporal structure of the whole trial.

Finally, our model did not take attentional effects into consideration. Wright and Dai (1998) showed that expectations influence AM detection performance (see also Conroy and Kidd, 2021). To the best of our knowledge, there is no model of auditory modulation processing able to reproduce such uncertainty effects.

CONCLUSIONS

The present study indicated that children from 5 to 11 years, as well as adults, showed an improvement in AM detection thresholds when presented with more AM cycles in the modulated target. Nevertheless, this effect is influenced by age, as the youngest children of 5-6 years displayed the worst thresholds when only 2 cycles were available, irrespective of the AM rate to detect. Furthermore, adults showed the best thresholds with 8 cycles compared to all age groups. These differences resulted in better temporal integration for AM detection in these two groups compared to the 7-8 and 10-11 years.

The fact that the youngest children were not affected by the absolute duration of the sounds suggested that their poorer thresholds did not relate only to a lack of sustained attention but may relate to inefficiencies, e.g., higher internal noise, in processing the temporal-envelope information when few cycles were available. Moreover, the reduced temporal integration observed between 7 and 11 years pointed towards additional constraints imposed by the limited memory buffer involved in AM processing with longer stimulus durations. Computational modelling confirmed that changes in late processing stages over age (e.g., a reduction of internal noise coupled with a reduction in memory noise) better explained changes in temporal integration between 5 and 11 years than changes in the early stages of AM processing. The model, however, did not account correctly for the data at 32 Hz, probably because of the short duration of the sounds and the dominance of the transient response of the simulated AM filters in this condition. The present study overall suggested that processing efficiency for AM continues to develop late into childhood.

APPENDIX

The model structure is similar to that used by Wallaert *et al*. (2017). The model had the following stages in sequential order:

1. a bank of five gamma-tone filters, one centered at the carrier frequency of the stimulus, and the remaining four centered at 1 and 2 ERB_N above and below the carrier frequency of the stimulus;
2. a ôbroken-stickô input-output function for the output of the gamma-tone filter tuned to the carrier frequency of the stimulus; the function is linear up to a knee-point of 30 dB SPL and compressive (using a power law with an exponent of 0.3) above;
3. half-wave rectification of all five frequency channels;
4. high-pass filtering (1st order 3 dB/oct roll-off, default cut-off value: 2.5 Hz) of all frequency channels to simulate the effects of short-term adaptation in the modulation domain (Tchorz and Kollmeier, 1999);
5. the signal of each frequency channel was passed to a filter-bank (1st order Butterworth filters) with 10 logarithmically-spaced channels tuned between 2 and 120 Hz (Moore et al., 2009), each with a *Q* factor of 1 (Ewert and Dau, 2000) to decompose the modulations of the processed signals, producing 50 channels;
6. the model preserved temporal-envelope phase at the output of modulation filters tuned below 6 Hz. The model discarded the envelope phase for channels above 6 Hz by passing only the absolute magnitude of the Hilbert transform of the outputs to the following stage;
7. two independent Gaussian noises (an ôadditiveô and a ômemoryô noise) were added consecutively to the output of all 50 channels; the first type of noise (ñadditive noiseò) had a constant standard deviation (SD) (Dau et al., 1997a); the second type of noise (ñmemory noiseò) was additive like the first one, but had an SD which was

multiplied by an exponential decay function to model echoic-memory limitation; the addition of this "memory noise" resulted in a weaker representation of the earlier part of the signal than the later and reduced temporal integration of envelope cues (Ardoint et al., 2008; Wallaert et al., 2017), disrupting the representation of longer duration stimuli more than shorter duration stimuli. The decay time constant was fixed at 1.4 s;

8. the final decision stage was based on a template matching process (Dau et al., 1997a). The model generated an "internal template" at the start of each staircase with the modulation depth set at the starting value and without any internal noise. The internal template was calculated as the difference between the internal representations of the target and reference stimuli, channel by channel. On each trial, the target and reference stimulus intervals were cross-correlated (channel by channel) with the template. The lags used in the cross-correlation were restricted to ± 1 target modulation cycle. The interval with the largest cross-correlation coefficient (summed across channels) was selected by the model.

Author Agreement Statement

We the undersigned declare that this manuscript is original, has not been published before and is not currently being considered for publication elsewhere.

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We understand that the Corresponding Author is the sole contact for the Editorial process.

He/she is responsible for communicating with the other authors about progress, submissions of revisions and final approval of proofs

Signed by all authors as follows:

Laurianne Cabrera, Irene Lorenzini, Stuart Rosen, Léo Varnet, Christian Lorenzi

ACKNOWLEDGMENTS

This work was supported by the European Unionõs Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No. 659204 held at the Department of Speech, Hearing and Phonetic Sciences, UCL and by Grant No. ANR-17-CE28-008 awarded to L.C. C.L. was also supported by Grants Nos. ANR-11-0001-02 PSL and ANR-10-LABX-0087. The authors wish to thank Gianna Li and Lucīa Sanz for help with testing at schools.

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