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Maturation of rapid auditory temporal processing and subsequent nonword repetition  
performance in children

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## Abstract

According to the rapid auditory processing theory, the ability to parse incoming auditory information underpins learning of oral and written language. There is wide variation in this low-level perceptual ability, which appears to follow a protracted developmental course. We studied the development of rapid auditory processing using event-related potentials (ERPs) elicited by tone pairs presented at varying inter-stimulus intervals (25, 50, 100, 200, and 400 ms) in a sample of children (N = 103) aged 7-9 years initially and again at 9-11 years. We also assessed their ability to repeat nonsense words at both time-points. The amount of difference between the ERP to single tones and paired tones (as assessed by the intraclass correlation coefficient, ICC) provided a measure of the brain's capacity to discriminate auditory information delivered at different presentation rates. Results showed that older children showed greater neural discrimination to tone pairs than younger children at rapid presentation rates, although these differences were reduced at slower presentation rates. The ICC at time 1 significantly predicted nonword repetition scores two years later, providing support for the view that rapid auditory temporal processing ability affects language development in typically-developing children.

*Keywords:* development, rapid auditory processing, children, language, ERPs

## Maturation of rapid auditory temporal processing and subsequent nonword repetition performance in children

A child's ability to distinguish rapidly presented auditory inputs continues to develop until early adolescence, as evidenced by performance on various psychophysical tasks (refs needed here). This aspect of auditory perceptual processing has generated considerable interest, particularly in view of the proposed relationship between early auditory temporal processing and the subsequent development of language. According to the rate-constraint processing theory of language and literacy development, children's ability to efficiently parse rapidly presented auditory material (in the order of tens of milliseconds) is related to the development of oral language skills, due to the fine-grained temporal resolution required to decode incoming speech into constituent phoneme units which, in turn, influence the child's ability to learn to read. Evidence in support for this theory was originally derived from the study of 6-9 year-old children with language impairments, who were able to identify the order of presentation of two 75 ms tones when presented at long interstimulus intervals (> 300 ms), but showed severely impaired performance when the tone pairs were presented at shorter inter-stimulus intervals (ISIs) (Tallal, 2004; Tallal & Gaab, 2006; Tallal, Miller, & Fitch, 1993). In a subsequent follow-up study of these same children, the deficits in the language-impaired group were more apparent for stimuli with rapid formant transitions (the first 43 ms of synthesised stop consonants ba and da) than for steady-state vowels of 250 ms duration (Tallal & Piercy, 1974). Alternative theoretical models have highlighted the importance of slower perceptual discrimination features corresponding to syllabic segmentation of speech (200 – 500 ms) in addition to phonemic-level segmentation in the development of phonological awareness in children (Goswami, 2011, Goswami, 2002; Goswami, Fosker, Huss,

Mead, & Szűcs, 2011). Additional research showed that behavioural and electrophysiological responses of infants to rapidly presented tones predicted language skills at 2-3 years of age, further supporting a role for rapid auditory processing in language development (Benasich et al., 2006; Benasich, Thomas, Choudhury, & Leppänen, 2002).

Nevertheless, there are several lines of research evidence indicating firstly, that rapid auditory temporal processing may not be causally related to the development of language skills as predicted by this theory and secondly, that variation in rapid auditory temporal processing explains only a relatively small proportion of the variance in language skills, indicating that other risk and/or protective factors play a significant role in the acquisition of language. Bishop and colleagues (Bishop, Carlyon, Deeks, & Bishop) used two measures of auditory temporal processing: threshold for detecting a tone occurring immediate after another tone (backward masking) and ability to distinguish a frequency modulated tone from a constant tone. They reported that Tallal's measure of rapid auditory processing administered to children aged 9-11 years was correlated with backward masking and frequency modulation thresholds two to three years later. However, there was large individual variation in thresholds, particularly for the backward masking task, and the relationship between the tasks was substantially reduced with practice. To examine the causal relationship between rapid auditory temporal processing and phonemic abilities, Johnson et al. (2009) assessed 108 children longitudinally on measures of rapid auditory temporal processing (backward masking) and phonological awareness initially at ages 5-6 years and again two to three years later. In contrast to the rate-constraint theory of language development outlined above, their path analysis indicated that phonological awareness at time 1 predicted backward masking levels at

time 2, but not the reverse. This result highlights the importance of top-down influences on behavioural measures of auditory temporal processing. However, performance on behavioural tasks such as backward masking have been shown to be particularly sensitive to attentional and motivational demands which change with age over the 6-11 year age range (Dawes & Bishop, 2008; Moore, Ferguson, Edmondson-Jones, Ratib, & Riley, 2010).

One way to minimise such extraneous effects on performance is to measure the brain's passive electrophysiological responses to auditory stimuli presented with no task demands. Distinctive event-related potentials (ERPs) can be recorded to by averaging responses to simple tone stimuli, but these differ markedly between children and adults. Progressive decreases in the latencies of the first positive peak has been reported between the ages of 5-6 years (80-85 ms) and 16 years (~ 50 ms), thought to reflect the increased speed of neural transmission resulting from increases in axonal diameter and myelination with development (Albrecht, Suchodoletz, & Uwer, 2000; Ponton, Eggermont, Kwong, & Don, 2000). Nevertheless, the identification of changes in latency for specific peaks is difficult given the dramatic changes in overall morphology and waveform complexity from early childhood to adulthood. If one's interest is in responses to rapid sequences of auditory stimuli, then matters are further complicated by the fact that one of the most prominent peaks of the adult ERP, a negative deflection around 100 ms (N1), is not clearly apparent in pre-adolescent children's ERPs when relatively rapid presentation rates (ISI < 1-2 s) are used (Čeponienė, Cheour, & Näätänen, 1998; Sussman, Steinschneider, Gumenyuk, Grushko, & Lawson, 2008). Sussman et al. showed that first positive peak (P1), which can be measured with presentation rates of 200-800 ms ISI, decreases in both amplitude and latency between 8 and 11 years of age.

Bishop and McArthur (2004) adopted a different approach, recording auditory ERPs to short duration single tones and tone pairs separated by ISIs of 20, 50, and 150 ms in a small sample of adolescents aged 11-19 years, including individuals with specific language impairment. Each stimulus (single tone or pair) was presented with stimulus onset asynchrony of 1084 ms, making it possible to compare the overall waveform for single tones vs. tone pairs. When the ISI between the members of a tone pair is very short, the overall ERP is only slightly different to that observed for a single tone. However, as the ISI between the members of the tone pair increases, the waveform alters shape, until, at the longest ISIs, a separate response to the second member of the pair can be observed in the ERP. (see Figure 1). The ability to differentiate a tone pair from a single tone can be quantified using the intraclass correlation (ICC) for the single tone and tone-pair waveforms, which will be high when discrimination is poor (waveforms are similar) and low when there is good discrimination (see Figure 1). Consistent with the notion of a relatively protracted maturational time course of rapid auditory temporal resolution, younger controls (11-13 years of age) failed to show a distinct neural response to the second tone of the pair when presented at ISIs less than 150 ms, whereas the older controls showed a distinct neural response at ISIs of 50 and 150 ms. Furthermore, the ERPs of the older language-impaired group resembled those of younger controls. Protracted maturational effects on the neural index of rapid auditory temporal processing were subsequently replicated when comparing a larger sample of typically developing children aged 7-9 years and adults over a larger range of SOAs from 25 - 800 ms (Fox, Anderson, Reid, & Bishop, 2010). In that study adults showed a distinct neural response to the second tone of the pair at all ISIs, whereas in children aged 7-9 years

no distinct neural response was elicited to tone pairs presented at ISIs shorter than 200 ms. The present study extends this finding by examining the maturational trajectory of this effect in children aged between 7 and 11 years. McArthur et al. (2009) reported that 7-12 year-old children with specific language or reading impairments showed less ‘typical’ brain responses than age-matched controls across various stimulus types, , yet there was no indication for increased impairment in the rapid tone condition, as predicted by the rapid temporal processing hypothesis. However, they did not examine the normal developmental time course of rapid auditory processing indices.

The first aim of the present study was to evaluate the maturational time course of auditory temporal resolution in children aged between 7 and 11 years by assessing the neural response to single tones vs. tone pairs presented at different inter-tone intervals. We predicted that younger children would show less ability than older children to differentiate two sequentially presented tones when the inter-tone interval was short, as evidenced by the similarity of their ERPs to a single tone vs. tone pair.

Our second aim was to examine the relationship between this maturational measure of auditory temporal resolution and subsequent language outcome as assessed by nonword repetition, given the dependence of this language task on processes of phonological segmentation and assembly, and given the sensitivity of this task to language impairment in young children (Archibald & Gathercole, 2007; Barry, Hardiman, & Bishop, 2009; Bishop et al., 1999; Boets, Wouters, van Wieringen, & Ghesquière, 2007; Coady & Evans, 2008). Despite the documented sensitivity of the nonword repetition task to specific language impairment (Bishop, North, & Donlan, 1996), the specific processes which contribute to this sensitivity are not well understood. Archibald and Gathercole (2007) showed that differences between SLI and control groups remained statistically significant after controlling for



estimates of short-term memory capacity, indicating that additional factors over and above short-term memory capacity contributed to the task's sensitivity in the detection of language impairments. They postulated that a key ability might be temporal processing of rapidly presented auditory multisyllabic material at input.

## **Methods**

### **Participants**

The sample was the same as that used by Bishop et al. (2011) to examine development of auditory ERPs to single tones. Data were excluded for two participants who did not do the nonword repetition task. Recruitment of children was by means of an invitation to the parents of children attending primary schools in the vicinity to participate in a longitudinal research program conducted over two years, with the first wave of testing in July 2007-2008 and the second wave of testing in July 2009-2010. The final sample included 62 younger children (age range 7 years 0 months to 8 years 4 months at time 1) and 41 older children (age range 8 years 8 months to 9 years 11 months at time 1), with roughly equivalent numbers of girls ( $n = 49$ ) and boys ( $n = 54$ ).

### **Tone stimuli**

Auditory stimuli were 1000 Hz, 50 ms duration sinusoidal tones (with 2 ms ramped onset and offset) presented at an intensity of 80 dB (SPL). In the single-tone trials a single auditory stimulus was presented whereas in the paired-tone trials, a second identical 50 ms tone was presented following an unfilled delay of 25, 50, 100, 200, 400, or 600 ms. Trials were presented in blocks at an inter-trial interval of 1.5 s, with random selection of each of the seven tone pairs within each block. Delivery of the first tone of the pair was randomly jittered between 0 and 200 ms from the start of the trial. A range of inter-tone intervals was selected to further examine the previously

reported finding that children showed a longer temporal window of integration than adults when presented with tone pair sequences (Fox et al., 2010).

Tone pairs with an inter-tone interval of 600 ms were included to provide a means of checking reliability of mean ERPs of individual participants. Because the second tone of the tone pair does not occur until after the ERP to the first tone has returned to baseline, the expectation is that the ERP to the first tone of the pair should be the same as the ERP to single tones. We quantified this by computing the ICC over the interval from stimulus onset to 400 ms post-stimulus between the single tone and the first tone of the tone pair presented at 600 ms ISI, as in Fox et al. (2010). Note that in this context we regard a high ICC as evidence of good reliability of the ERP, whereas when analysing temporal resolution, a *low* ICC is an indication of maturity, because it reflects differential responses to a tone pair vs a single tone.

## **Procedure**

Participants completed the nonsense words repetition subtest of the NEPSY according to standardised procedures (Korkman, Kirk, & Kemp, 1998). For the EEG recording, an electrode cap was fitted and participants were presented with the auditory stimuli while they silently read or played electronic games. They were instructed to ignore the tone sequences, but to remain quiet and still throughout the recording session. Children attended the unit on two consecutive days and a comprehensive assessment of their cognitive, emotional, and social functioning was obtained. For half of the children tested, the nonsense word repetition task was administered on the first day of attendance and the EEG recording on the second day, whereas for the remainder of the children the EEG was recorded on day 1 and the nonsense word repetition test was administered on day 2.

## **EEG acquisition and analyses**

The electroencephalogram (EEG) was recorded continuously from 33 scalp locations using an electrode cap (EasyCap, Montage 40, excluding TP9 and TP10), referenced to the right mastoid. Electrodes were also placed above and below the left eye, and on the left mastoid, with an averaged mastoid reference digitally computed offline. The ground was located at site AFz. Data were amplified with a NuAmps 40-channel amplifier, and digitized at a sampling rate of 250 Hz. The analog signal was filtered off-line with a 2-30 Hz, zero phase shift band-pass filter (12 dB down) as detailed in Fox et al. (2010). Ocular artifact reduction was performed on the continuous EEG with regression-based subtraction of the averaged blink artefact identified in the bipolar VEOG channel. Epochs encompassing an interval from 50 ms prior to the onset of the first tone in the pair to 1000 ms post-stimulus were extracted and trials contaminated by artifact exceeding 150  $\mu$ V rejected from the individual subject ERP averages.

The similarity of the evoked responses to the tone pairs presented at increasing ISIs was compared by computing the intra-class correlation coefficient (ICC) between the individual's single tone ERP and the ERP elicited to the tone pairs presented at increasing ISIs, consistent with the approach reported by Bishop and colleagues (Bishop & McArthur, 2004; Fox et al., 2010). We focussed on the overall waveform similarity index given the difficulties in identifying peak latencies and amplitudes with overlapping neural responses to rapidly presented stimuli. The frontal midline site (Fz) was selected for analysis given that the effects of ISI and the developmental changes in response to single tones are maximal at that site (Bishop, Anderson, Reid, & Fox, 2011; Fox et al., 2010). The ICC provides a measure of the similarity of the waveform amplitude and shape, with *higher* values representing greater similarity between the ERPs elicited to the different tone-pair conditions. ICC should be low for

conditions where the tone-pairs are processed differently to the single tones. To normalise the distribution of scores on this variable, the Fisher's z-transformation was applied, extending the maximum value attainable.

## Results

The grand averaged waveform for the younger and older groups at initial testing (time 1) and two years later (time 2) are shown in Figure 1. Visual inspection of the waveforms suggests that there are marked differences in the morphology of the waveforms elicited in response to tones presented at rapid ISIs (25-100 ms) compared to the waveforms elicited in response to tones at longer ISIs (200 and 400 ms). The ERPs elicited in response to rapid tone pairs show an enhanced negativity relative to the single tone, peaking approximately 150 ms after the onset of the second tone in the pair. For inter-tone intervals of 200 or 400 ms, there is no evidence of this negative enhancement, and instead a distinct P1 is elicited approximately 100 ms after the onset of the second tone. The ICC provides an overall measure of dissimilarity between two waveforms, and is sensitive to variation in the amplitude, latency, and overall shape of the ERPs. As such, although this measure does not allow us to distinguish the specific processes that change with age or presentation rate, it provides a particularly sensitive composite measure for charting global maturational differences. The ICCs over the interval from 0-400 ms between the single and paired-tone ERPs were computed for each participant and condition and submitted to analysis of variance (ANOVA) with repeated measures factors of session (time 1, time 2) and ISI (25, 50, 100, 200, and 400 ms), and the between-subjects factor of age at initial recruitment. Follow-up main effects involving the factor of ISI were examined by comparing the ICC over the 0-400 ms interval at each ISI with that of the 400 ms tone pair condition. Note that we expect the ICC in the latter condition to

be high, given that the interval examined precedes the onset of the second tone. Mean and SD ICCs for each of the groups and presentation rates are presented in Table 1. The ICCs were significantly lower for all paired-tone waveforms than for the 400 ms ISI waveform (main effect of ISI  $F(4,404) = 26.17, p < .001$ ), and the effect of age differed as a function of presentation rate (session x ISI interaction,  $F(4,404) = 3.05, p = .019$ ). Follow-up comparisons examining the effect of session at each ISI indicated that the children showed significantly lower ICCs at time 2 than at time 1 at rapid presentation rates (25 ms ISI,  $F(1,102) = 5.28, p = .024$ , partial  $\eta^2 = .05$ ; 50 ms ISI,  $F(1,102) = 10.77, p = .001$ , partial  $\eta^2 = .10$ ), but this effect did not approach statistical significance for tones delivered at slower presentation rates (200 and 400 ms ISIs;  $F(1,102) < 1$ ). This result provides support for the hypothesis that rapid auditory temporal processing undergoes significant maturation over the two-year period from roughly 8 years of age to 10 years of age. Note, however, that although this effect was clearly apparent in the repeated-measures comparison of session 1 vs session 2, it was not evident when age groups were compared cross-sectionally, and there was no indication that this developmental change was more marked in either the younger or older subsamples (main effect of age group,  $F(1,101) < 1$ ; ISI x session x age group interaction  $F(4,404) < 1$ ).

The neural response to tone pairs delivered with inter-tone interval of 50 ms was highly sensitive development in our sample, so we selected this condition to evaluate the second research question, namely, whether early rapid auditory temporal processing predicted subsequent nonword repetition performance. The mean performance on the nonword repetition subtest of the NEPSY at time 1 was within the average range for the younger and older age groups, as can be seen from inspection of the raw scores and standard scores in Table 1. Raw scores increased at time 2, and this

increase was greater for the younger group (main effect of session,  $F(1,101) = 82.5$ ,  $p < .001$ , partial  $\eta^2 = .450$ ; session x age group interaction,  $F(1,101) = 9.61$ ,  $p = .003$ , partial  $\eta^2 = .087$ ). In the regression analysis, raw nonword repetition performance at time 2 was treated as the dependent variable, and the ICC to 50 ms ISI tone pairs at time 1 was fitted as a predictor after controlling for nonword repetition performance at time 1. Nonword repetition scores at time 1 was a significant predictor of performance two years later ( $R^2 = 0.09$ ,  $F(1,101) = 9.77$ ,  $p = .002$ ). Furthermore, after controlling for time 1 nonword repetition scores, the 50 ms ICC at time 1 added significantly to the prediction of nonword repetition scores at time 2 ( $F(1,100) = 7.55$ ,  $p = .007$ ,  $R^2$  change = .064).

## Discussion

As predicted, the neural response elicited to rapidly presented stimuli showed a protracted maturational time course, with changes identified over the two-year period between approximately 8 and 10 years of age. This result extends findings previously reported by Bishop and colleagues who showed a similar developmental trend in 11-13 year-olds compared to 14-19 year-olds (Bishop et al., 2011; Bishop & McArthur, 2004), showing that the electrophysiological index measured to simple rapidly presented non-speech stimuli is a particularly sensitive measure of this developmental change. Nevertheless, numerous studies have failed to observe improvements in auditory processing over this age range (Bailey & Snowling, 2002) and it seems likely that differences in methodology can account for this discrepancy. Additionally, when rapid auditory temporal processing is assessed using experimental behavioural tasks, such as backward masking and frequency modulation, the performance of children of this age has been shown to be particularly influenced by attentional and motivational factors (Dawes & Bishop, 2008; Moore et al., 2010).

Therefore, the validation of indices of neural development that can be elicited during passive conditions is vitally important when attempting to chart the development trajectory of auditory processing in children over this age range.

As highlighted previously, the ICC provides a measure of global dissimilarity of the neural response to incoming information, and does not identify the locus of the differences. Lower ICCs will be observed following changes to waveform shape and/or the latency and amplitude of peaks and troughs in the ERPs. Previous research has shown increasing maturation over a protracted time course in a number of specific processes involved in analysing rapidly presented incoming auditory information. For example, developmental changes have been shown in the ability to discriminate simultaneously presented streams of auditory material (Alain, Theunissen, Chevalier, Batty, & Taylor, 2003; Sussman et al., 2008), the ability to segregate temporally distinct sources of information (Bishop & McArthur, 2004; Fox et al.), the inhibition of responses to information outside the auditory temporal window of integration (Fox et al., 2010), and the synchronisation of phasic oscillations within the brain at specific frequencies to incoming stimuli (Bishop et al., 2011). The present results add to this body of research and show that there are marked developmental changes in children's ability to parse an incoming auditory stream into objects. That is, at faster ISIs (< 200 ms) the younger 7-9 year-old children continued to integrate the tone pair as a single auditory object, whereas the older 9-11 year-old children showed two distinct neural responses to the tone pairs. This difference was most pronounced when the interval between successive tones was 50 ms, and raises the question of whether the critical feature is the interval between tones or whether the critical feature is the duration of the auditory object (in this case, 150 ms). These electrophysiological techniques

provide a non-invasive and effective way to examine the nature of auditory temporal processing throughout development.

An additional prediction derived from the rapid auditory temporal processing hypothesis (Tallal, 2004; Tallal & Gaab, 2006; Tallal et al., 1993) was that the individual's capacity to process rapidly incoming auditory information would relate to the ability to subsequently develop effective oral language skills. More recent developmental studies have suggested that the timescale of the rapid auditory processing changes corresponds more closely to the segmentation of syllables (150 – 200 ms) rather than initial phonemes (~ 50 ms), as originally proposed by Tallal and colleagues (Goswami, 2011). Our results provided support for the hypothesis that the child's facility at decoding relatively low-level auditory perceptual features contributes to subsequent language development, showing that a small but statistically significant proportion of the variance in nonword repetition performance was explained by the neural index of rapid auditory temporal processes two years prior to assessment. However, our results do not directly address whether the timescale relates more closely to phonemic or syllabic segmentation of the speech stream, given that repetition of multi-syllabic nonsense words incorporates both aspects. Inclusion of additional behavioural tasks that separate these two aspects of linguistic processing is therefore warranted. Electrophysiological indicators of rapid auditory processing in infants have been shown to predict subsequent language outcome two to three years later, consistent with the present findings (Benasich et al., 2006; Benasich et al., 2002). Other longitudinal studies have failed to show this relationship (Bishop et al., 1999; Boets et al., 2007; Johnson et al., 2009) although again the attentional demands of tasks requiring overt behavioural responses to estimate neural sensitivity to rapidly presented material could explain the lack of relationship in these studies. It is



therefore important to evaluate rapid auditory processing using measures that are not sensitive to task demands.

In the present study the amount of variation in subsequent language skills accounted for by rapid auditory temporal processing index was quite low, consistent with the notion that there are a number of factors determining language proficiency during childhood (Bishop et al., 1999). The current results suggest that one of these is the brain's facility at decoding rapidly presented auditory information. Given that this relationship was evident when presenting pure-tone stimuli, our findings suggest that these effects do not depend on specific phonological features (Mody, Studdert-Kennedy, & Brady, 1997), although it is plausible that individual differences in the processing of phonological material accounts for additional variance in language outcomes, as indicated by prior research with polysyllabic stimuli (Barry et al., 2009). An important future research direction will be to examine whether the relationship between rapid temporal processing and the child's subsequent ability to learn language identified in the present study extends from the auditory domain to other modalities, whilst taking in to account the developmental trajectories of the sensory and cognitive systems under investigation as recommended by Karmiloff-Smith (2010).

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Table 1. Mean Scores (and Standard Deviations) for Younger and Older Age Groups at Baseline and Follow-up and Effect Sizes of the Within-subjects Age Comparison on the Intra-class Correlation Coefficient (ICC).

	Younger		Older		Partial $\eta^2$
	Time 1	Time 2	Time 1	Time 2	
Age (years)	7.5 (0.29)	9.5 (0.29)	9.5 (0.28)	11.5 (0.29)	
Nonword repetition					
Raw score	29.9 (6.2)	38.0 (5.2)	31.9 (5.1)	35.9 (6.5)	
Standard score	10.1 (2.4)	12.4 (2.7)	9.6 (2.3)	10.6 (2.9)	
ICC					
25 ms ISI	0.92 (0.38)	0.82 (0.42)	0.89 (0.35)	0.79 (0.42)	.049
50 ms ISI	1.02 (0.37)	0.88 (0.45)	1.04 (0.35)	0.89 (0.38)	.096
100 ms ISI	1.01 (0.45)	0.99 (0.38)	1.04 (0.39)	0.92 (0.39)	.024
200 ms ISI	0.98 (0.42)	0.96 (0.44)	0.94 (0.39)	0.88 (0.37)	.006
400 ms ISI	1.12 (0.39)	1.14 (0.43)	1.14 (0.45)	1.17 (0.43)	.003

Figure caption.

Figure 1. Grand averaged ERP waveforms elicited in response to the single tone (dashed line) and the paired tone (solid line) stimuli at Fz for the younger group (mean age = 7.5 years, SD = 0.28 at time 1) and the older group (mean age = 9.5 years, SD = 0.29 at time 1). The grey rectangular boxes beneath each waveform indicate the temporal sequence of stimulus presentation in each condition. Amplitude of the ERP (in  $\mu\text{V}$ ) is represented on the y-axis, with negative voltages plotted as downward deflections. Time (in ms) is represented on the x-axis, with time zero corresponding to the onset of the tone.

