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Hemispheric Asymmetries in Rapid Temporal Processing at Age 7 Predict Subsequent Phonemic Decoding 2 years later: a longitudinal event-related potential (ERP) study

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Abstract

The asymmetric sampling in time hypothesis (AST) suggests that the left and right secondary auditory areas process auditory stimuli according to different sampling rates (Poeppel, 2003). We investigated whether asymmetries consistent with the AST are observable in children at age 7 and whether they become more pronounced at age 9. Data were collected from 50 children who attended a 2-day research program at age 7 (26 boys, 24 girls; $M = 7.50$ years, $SD = 0.30$) and were followed up 2 years later ($M = 9.47$ years, $SD = 0.30$). At both time points, children were presented with tone-pairs, each composed of two 50 ms, 1000 Hz, sinusoidal tones separated by inter-stimulus intervals (ISIs) of 25, 50, 100, or 200 ms. Stimuli were presented binaurally whilst the EEG was recorded. There was no significant effect of age on Ta or Tb responses. Tb responses to the second tone of tone-pairs indicated a left-hemisphere preference for rapidly presented stimuli (50 ms ISI) and a right hemisphere preference for more slowly presented stimuli (100 and 200 ms ISI). The results provide evidence that auditory areas of the left hemisphere preferentially respond to fast temporal rates, and those of the right hemisphere preferentially respond to slow temporal rates in children at age 7 and 9. In 7-year-old children, leftward lateralization of responses to rapidly presented tones predicted better phonemic decoding ability 2 years later, which suggests that hemispheric specialization may be a precursor for subsequent phonemic decoding skills.

Highlights:

1. We examined Ta and Tb responses to rapid and slow tone-pairs in children
2. Tb responses to rapid (50 ms) tone-pairs were enhanced over the left hemisphere
3. Tb responses to slow (100-200 ms) tone-pairs were enhanced over the right hemisphere
4. Lateralisation of Tb for rapid tones at age 7 predicts phonemic decoding at age 9.

Keywords: Tb, asymmetric sampling in time, temporal integration, hemispheric asymmetry, event-related potential, auditory processing, phonemic decoding, children

1 **1. Introduction**

2 **1.1. Multi-time resolution framework of speech processing**

3 Speech is a rich composition of both temporal and spectral modulations. Temporal cues are
4 known to contribute significantly to the intelligibility of speech (Luo and Poeppel, 2007), even when the
5 signal is spectrally degraded. We use temporal cues to identify auditory objects such as phonemes and
6 syllables, thus, sensitivity to temporal modulations in the phonemic and syllabic timescales is necessary
7 for speech perception. Current research supports a multi-time resolution model of temporal processing
8 for speech perception called the Asymmetric Sampling in Time (AST) hypothesis (Poeppel, 2003). The
9 AST suggests that functional asymmetries of the left and right auditory areas facilitate the processing of
10 the fast and slow modulations present in speech (phonemic/segmental and syllabic/suprasegmental).
11 Poeppel (2003) proposed that temporal integration windows of either a short (25-50 ms) or long (200-
12 250 ms) duration provide an intrinsic framework by which we sample auditory information in chunks or
13 phonological units. He further postulated that the privileged sampling rates associated with the temporal
14 integration windows are synonymous with the intrinsic oscillatory rates of neuronal ensembles in the left
15 and right auditory areas. According to the AST, neuronal ensembles in both the left and right primary
16 auditory areas are tuned to rapid temporal modulations 25-50 ms (20-40 Hz), which potentially
17 facilitates the higher-order decomposition of the signal into fast and slow modulations. In the secondary
18 auditory areas, the neuronal ensembles in the left and right hemispheres are differentially tuned to rapid
19 (25-50 ms = 20-40 Hz), and slow (200-250 ms = 4-5 Hz) modulations, respectively. The AST
20 hypothesis proposes a hierarchical, intrinsic neural framework, which is optimally suited to the
21 segmental and suprasegmental timescales of speech, and is necessary for the perception of phonemes
22 and syllables (Poeppel, 2003).

23 Numerous studies have investigated the predictions of the AST in adults using a range of
24 neuroimaging techniques such as functional magnetic resonance imaging (fMRI; Boemio et al., 2005),
25 electroencephalography (EEG; Clunies-Ross et al., 2015), simultaneous fMRI and EEG (Giraud et al.,
26 2007), and magnetoencephalography (MEG; Luo and Poeppel, 2007; 2012). In general, results have
27 supported the AST in that there is a leftward preference for the processing of rapid modulations and a
28 rightward preference for slow modulations. For example, Giraud and colleagues (2007) used
29 simultaneous EEG and fMRI to demonstrate that spontaneous fluctuations in EEG power in the gamma
30 range (28-40 Hz) best correlated with endogenous neural activity in the left auditory cortex and

1 fluctuations in the theta (3-6 Hz) range best correlated with endogenous neural activity in the right
2 auditory cortex. Despite substantial evidence for asymmetric temporal processing in adults, the
3 developmental trajectory of temporal processing asymmetries is still unknown. Importantly, the role
4 such asymmetries may play in the development of complex linguistic abilities is poorly understood
5 (Vanvooren et al., 2014).

6 **1.2. Auditory ERPs and temporal processing**

7 In the current study, we used EEG to investigate hemispheric asymmetries in temporal
8 processing in children. As cortical processing of auditory signals occurs in the order of milliseconds,
9 techniques such as EEG or MEG provide high temporal resolution which is necessary for the detailed
10 analysis of such processes. However, previous research indicates that the activity of the auditory cortex
11 gives rise to both tangential (vertical) and radial (lateral) dipoles (Ponton et al., 2002). Whilst EEG is
12 sensitive to both tangential and radial dipoles, MEG is primarily sensitive to tangential dipoles (Irimia et
13 al., 2012). This difference is particularly important as the tangential dipole has been localised to the
14 superior surface of the temporal lobe (primary auditory cortex and belt areas of secondary auditory
15 cortex), and the radial dipole has been localised to the lateral surface of the temporal lobe (parabelt areas
16 of secondary auditory cortex) (Ponton et al., 2002; Ruhnau et al., 2011). The poor sensitivity of MEG to
17 radial dipoles means that the use of this technique in auditory processing research may mask critical
18 neural activity of secondary auditory areas. EEG is also a non-invasive, cost-effective neuroimaging
19 technique that is suitable for use in a wide range of age groups, from infants to the elderly. It is therefore
20 a valuable neuroimaging technique that can be used for a wide range of experimental paradigms and
21 populations.

22 The obligatory ERPs elicited by auditory stimuli are divided into fronto-central, and temporal
23 components, generated by the tangential and radial dipoles, respectively (Albrecht et al., 2000; C Ponton
24 et al., 2002). In previous years, it was suggested that the temporal components were simply an inversion
25 of the components observed at fronto-central sites, however, differences in the maturation rates (Bishop
26 et al 2011) and source dipoles strongly suggest that fronto-central and temporal ERPs are dissociable
27 (Ponton et al 2002).

1 **1.2.1. Fronto-central auditory ERPs**

2 In adults, the fronto-central ERP waveform is the most often reported, and contains the P1 and N1.
3 The P1 is a positive deflection that peaks between 50-150 ms in adults, and 100-300 ms in children. It is
4 present from infancy and is thought to reflect early auditory processing in the cortex (Campbell et al.,
5 2011; Shafer et al., 2015). The N1 is a negative deflection that peaks between 50-200 ms. It is the most
6 well-studied of the auditory ERPs due to its prominence in adults, however, the N1 is not clearly
7 observed in children until approximately 10 years of age (Ruhnau et al., 2011). The P1-N1 components
8 are proposed to reflect acoustic feature processing (Wagner et al., 2013; Wagner et al., 2017)
9 predominantly in the primary auditory cortex (Albrecht et al., 2000; Bishop et al., 2011; Ruhnau et al.,
10 2011).

11 **1.2.2 Temporal auditory ERPs**

12 The temporal ERP waveform contains the Ta, and Tb components, commonly referred to as the
13 T-complex. It is the most prominent ERP component in children, and becomes less prominent
14 throughout adolescence and adulthood when the N1 becomes more prominent. The Ta is a positive
15 deflection that occurs between approximately 140-170 ms post-stimulus onset in childhood (Shafer et
16 al., 2015). Whilst the T-complex is proposed to reflect the activity of secondary auditory areas due to the
17 orientation of the dipole, some studies have localised the Ta to the primary auditory cortex (Bishop et
18 al., 2011), and others report origins in secondary auditory areas (Ponton et al., 2002). The Tb is a
19 negative deflection that peaks between 140 and 200 ms in children, and has been localised to the
20 secondary auditory cortex (Albrecht et al., 2000; Shafer et al., 2015; Tonnquist-Uhlen et al., 2003).

21 The T-complex has been implicated as a potential component for identifying individuals at risk
22 of language difficulties (Shafer et al., 2011; Tonnquist-Uhlen et al., 2003). Like the P1-N1, the T-
23 complex reflects acoustic feature processing, but is also shown to respond differentially depending on
24 the phonological content (Wagner et al., 2013) and temporal rate of stimuli (Clunies-Ross et al., 2015).
25 The Ta appears less identifiable in individuals prior to the age of 7 years, and continues to increase in
26 amplitude before reaching peak amplitude at age 11 (Shafer et al., 2015; Tonnquist-Uhlen et al., 2003).
27 Some studies report that the Tb is identifiable from approximately 6 years of age (Tonnquist-Uhlen et
28 al., 2003), whereas others report that it is more stable across individuals from age 7-8 years (Shafer et
29 al., 2015).

1 **1.2.3 Functional utility of auditory ERPs**

2 As fronto-central and temporal ERP components reflect areas of the primary and secondary
3 auditory areas, respectively, they can be used to differentiate between acoustic feature processing and
4 higher-level auditory processing. Clunies-Ross et al. (2015) examined asymmetries in N1, Ta and Tb
5 responses elicited by tone-pairs with inter-stimulus intervals (ISIs) of 50 and 200 ms. No asymmetries
6 were observed for N1 and Ta responses to rapid and slow tone-pairs. The asymmetries in the Tb
7 component supported left hemisphere preference for the processing of rapidly presented stimuli (50 ms)
8 and a right hemisphere preference for slowly presented stimuli (200 ms). Their findings indicated that
9 stimuli are processed in a hierarchical manner according to temporal features and also showed that the
10 Tb was particularly important when investigating functional asymmetries in temporal processing.

11 A previous study by Fox et al. (2012) examined the development of temporal processing in
12 children using the fronto-central components. The children were tested at 7- and 9 years, and 2 years
13 later, at 9 and 11 years. They used intra-class correlations (ICCs) to compare the fronto-central
14 waveforms elicited by single-tones and tone-pairs with varying ISIs. High ICCs indicated a low degree
15 of discrimination between tones, whilst low ICCs indicated a high degree of discrimination between
16 tones. They observed significant changes from time 1 to time 2 in ICCs for rapidly presented tone-pairs,
17 suggesting that the temporal discrimination of rapid tones improved between 7 and 9 years, and between
18 9 and 11 years. They also examined the relationship between rapid temporal processing and nonword
19 repetition. They found that ICCs for 50 ms ISI tone-pairs at the initial testing was a significant predictor
20 of nonword repetition two years later. They suggested that rapid temporal processing abilities contribute
21 to auditory decoding in subsequent years, consistent with the idea that early auditory temporal
22 processing likely facilitates the ability to discriminate phonological units (Poeppel, 2003).

23 **1.3. Current study aims and hypotheses**

24 The purpose of the current study was to extend the findings of Clunies-Ross et al. (2015) and
25 Fox et al. (2012) in two ways. Our first objective was to look at the development of hemispheric
26 asymmetries in temporal processing in children. Although Fox et al. (2012) examined the development
27 of rapid temporal processing; they looked at fronto-central components only, and did not examine
28 hemispheric asymmetries. Of the previous studies that have examined temporal processing asymmetries,
29 most have focused on younger children (≤ 5 years of age), and have been relatively inconsistent.

1 Thompson et al. (2016) observed leftward lateralisation of high-frequency endogenous oscillations (20-
2 50 Hz) in children aged 3 to 5 years-old, while Vanvooren and colleagues (2014) observed no
3 lateralisation for processing of 20 Hz modulations in children of the same age. Rightward lateralisation
4 of temporal processing for slow modulations has been observed in infants (Telkemeyer et al., 2009) and
5 children aged 5 years-old (Vanvooren et al., 2014). However, Thompson et al. (2016) found no
6 lateralisation of low-frequency endogenous oscillations in children aged 3-5 years old. Thompson et al.
7 (2016) suggested that the bilateral representation of low-frequency oscillations (3-7 Hz) in 3-5-year-old
8 children might be due to the further maturation of the relevant neuronal populations in the right
9 hemisphere in mid-to-late childhood.

10 Given the mixed findings in younger children, the developmental trajectory remains unclear, and
11 may be clarified with the investigation of temporal processing asymmetries in older children. As
12 Clunies-Ross et al. (2015) demonstrated the utility of temporal auditory ERPs for detecting functional
13 asymmetries in temporal processing, we examined the Ta and Tb responses to tone-pairs with short (25,
14 50 ms) and long (100, 200 ms) ISIs in children at age 7, and again 2 years later at age 9. Previous studies
15 have observed marked development of T-complex components (Bishop et al., 2011; Tonnquist-Uhlen et
16 al., 2003) and associated complex linguistic skills between 7 and 9 years of age (Vandewalle et al.,
17 2012). Therefore, hemispheric asymmetries in this age band could provide further clarification regarding
18 the emergence of functional asymmetries and may also inform the relevance of these asymmetries for
19 higher-order linguistic processes.

20 Our second objective was to investigate whether the lateralisation of rapid temporal processing to
21 the left secondary auditory areas (as indexed by the Tb) is associated with the subsequent development
22 of phonological representations necessary for decoding letter strings. Poeppel (2003) suggested that the
23 hierarchical decomposition of auditory signals facilitates the isolation and identification of
24 distinguishable units within the speech signal. The ability to isolate segmental and suprasegmental units
25 of speech is essential for the development of phonological skills, such as phonemic decoding (Goswami,
26 2011; Vanvooren et al., 2014). Like the nonword repetition task used by Fox et al. (2012), phonemic
27 decoding also requires the use of phonological output lexicon and oromotor skills, but does not require
28 auditory discrimination of sounds. Furthermore, phonemic decoding requires the mapping of graphemes
29 to phonological representations, and taps the integrity of phonological representations as it requires the
30 ordering and combining of these representations according to phonological rules (Wolf et al., 1998). In

1 light of the relationship between the ERP index of rapid auditory processing and subsequent nonword
2 repetition observed by Fox et al. (2012), we hypothesised that the leftward lateralisation of rapid
3 temporal processing (indexed by the Tb) at age 7 would be associated with subsequent phonemic
4 decoding at age 9.

5 **2. Methods**

6 **2.1. Participants**

7 The current study examined the archival auditory ERP data of children reported in Fox et al.
8 (2012) and Bishop et al. (2011). The children attended Project K.I.D.S., a 2-day research program aimed
9 at investigating the cognitive, social and emotional development of children. Children were initially
10 tested at age 7 years in July of 2007 or 2008, and were retested 2 years later in July of 2009 or 2010.
11 Parents provided informed written consent for their children to take part in the study. Data were
12 excluded from individuals with a history of neurological disorders, and from whom reliable auditory
13 evoked responses were not elicited by the single tone at sites of interest (Fox et al., 2010). The final
14 sample consisted of 50 children (26 boys, 24 girls; $M = 7.50$ years, $SD = 0.30$, range 7 years 0 months to
15 8 years 4 months; $M = 9.47$ years, $SD = 0.30$, 9 years 0 months to 10 years 4 months).

16 **2.2. Auditory stimuli**

17 The auditory stimuli were composed of standard 50 ms, 1000 Hz sinusoidal tones with 2 ms
18 ramped onset and offset. Sound intensity was calibrated using a 1-second continuous 1000 Hz sinusoidal
19 80 dB SPL tone measured by a Bruel and Kjaer sound level meter. There were six stimulus types: a
20 single tone stimulus, and five tone-pair stimuli. The tone-pairs were each composed of two tones that
21 were separated by varying interstimulus intervals (ISIs; 25, 50, 100, 200, and 600 ms). Each trial was set
22 to 1500 ms in duration, and the stimulus onset times were randomly jittered between 0-200 ms from the
23 start of each trial (Woldorff, 1993). In addition, the 600 ms ISI tone-pairs were presented to determine
24 whether a reliable auditory ERP was elicited (Fox et al., 2010; Fox et al., 2012). The maturation of
25 auditory ERPs elicited by single tones has been reported previously by Bishop et al. (2011), and auditory
26 ERPs elicited by tone-pairs (Fz only) have been reported previously by Fox et al. (2012).

1 2.3. Measurement of phonological processing

2 The Sight Word Efficiency and Phonemic Decoding Efficiency subtests of the Test of Word
 3 Reading Efficiency (TOWRE) measure sight word reading fluency and phonological decoding
 4 (Torgeson et al., 1999). The Sight Word Efficiency subtest is composed of four columns of real words
 5 (104 words in total) and the Phonemic Decoding Efficiency subtest is composed of three columns of
 6 nonwords (63 nonwords in total). For each subtest the participant must read aloud as many items as they
 7 can in 45 seconds. For each subtest, the raw score is the number of items pronounced correctly in 45
 8 seconds.

9 The TOWRE has high internal consistency between 0.86 and 0.98 (Torgeson et al., 1999) and
 10 high test-retest reliability between 0.82 and 0.97 (Tanna, 2009). The Sight Word Efficiency and
 11 Phonemic Decoding Efficiency subtests also have high inter-rater reliability ($r > 0.99$ and 0.98 ,
 12 respectively; Marinus et al., 2013). The TOWRE has adequate construct validity, correlating highly with
 13 other measures of reading ability such as the Woodcock Reading Mastery Tests-Revised (Sight Word
 14 Efficiency $r = 0.89$ to 0.91 ; Phonemic Decoding Efficiency $r = 0.89$ to 0.91 ; Tanna, 2009). The
 15 descriptive statistics for Sight Word Efficiency and Phonemic Decoding Efficiency scores are presented
 16 in Table 1.

17 Table 1.

18 *Descriptive Statistics of Raw Score Performance on the Sight Word Efficiency and Phonemic Decoding*
 19 *Efficiency Subtests at Age 7 and Age 9.*

| | Subtest of the TOWRE | |
|-------|-----------------------|------------------------------|
| | Sight Word Efficiency | Phonemic Decoding Efficiency |
| | <i>M (SD)</i> | <i>M (SD)</i> |
| Age 7 | 53.86 (13.19) | 25.62 (9.71) |
| Age 9 | 70.80 (6.82) | 39.90 (8.43) |

20 $N = 50$

21 In the present study, performance on the Sight Word Efficiency and Phonemic Decoding
 22 Efficiency subtests improved significantly from 7 to 9 years of age $t(49) = 11.37, p < .001, d = 1.61$, and
 23 $t(49) = 14.51, p < .001, d = 2.05$, respectively.

1 **2.3. Procedure**

2 Participants were fitted with an EasyCap™ at the beginning of each testing session. Auditory
3 stimuli were presented to participants binaurally via a set of Sennheiser HD 265 adjustable headphones
4 placed over the ears in a quiet room. A passive task was used to reduce the influence of attention to
5 stimuli on ERP amplitudes (Lang et al., 1995; McArthur et al., 2003; Naatanen, 1995). Participants were
6 instructed to ignore the tones and were provided with reading materials (picture books with minimal
7 text) and hand-held electronic games (audio switched off) to aid their distraction. If at any time the
8 participant's chosen activity was interfering with the EEG recording (e.g. excessive eye movements),
9 they were instructed to change activities. Stimuli were presented binaurally to avoid asymmetric
10 activation of the left and right auditory cortices caused by monaural presentation (Mahajan and
11 McArthur, 2013). Participants completed the TOWRE Sight Word Efficiency test first, followed by the
12 Phonemic Decoding Efficiency subtest as in the standardized administration instructions.

13 **2.4. EEG data acquisition**

14 Data were acquired using SCAN™ 4. Electrophysiological activity was continuously recorded
15 via electrodes located at 33 scalp locations (Fp1, Fp2, F3, F4, F7, F8, Fz, FC1, FC2, FC5, FC6, FCz,
16 FT9, FT10, C3, C4, Cz, T7, T8, CP1, CP2, CP5, CP6, P3, P4, P7, P8, Pz, PO9, PO10, O1, O2, Iz).
17 Channel impedances were limited to below 10 kΩ prior to recording. The EEG was amplified using a
18 NuAmps 40-channel amplifier, digitised at a sampling rate of 250 Hz, and filtered online using a 0.01-
19 30 Hz band-pass filter. AFz was set as the ground and the electrode located at the right mastoid was set
20 as the reference. Data were processed offline using SCAN™ 4. A common-averaged reference was
21 calculated offline, and data were re-referenced to the common-averaged reference. Vertical ocular
22 artifacts were removed via a regression algorithm (Semlitsch et al., 1986) using the recordings from two
23 ocular leads placed 2 cm above and below the left eye. The EEG was digitally filtered offline using a 1-
24 30 Hz zero phase-shift band-pass filter (12 dB roll-off) (Bishop et al., 2011). Epochs were segmented
25 from 100 ms pre-stimulus onset to 1000 ms post-stimulus onset. Averaged waveforms were baseline-
26 corrected around the 100 ms pre-stimulus interval. Epochs that contained artifacts exceeding $\pm 150 \mu\text{V}$
27 were rejected. The mean numbers of epochs included per participant after epoch rejection are included
28 in Table 2.

1 Table 2.

2 *Mean Number of Epochs Per Participant at Age 7 and Age 9 for the Single Tone and Tone-pairs.*

| | Stimulus | | | | | |
|-------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| | Single | 25 ms | 50 ms | 100 ms | 200 ms | 600 ms |
| Age 7 | 158.98 (19.58) | 158.64 (20.10) | 158.56 (19.99) | 158.60 (19.51) | 159.58 (20.09) | 158.54 (19.93) |
| Age 9 | 163.82 (18.50) | 163.22 (18.03) | 163.34 (18.69) | 163.68 (18.45) | 164.52 (18.60) | 163.80 (18.27) |

3 $N = 50$

4 **2.6. Correction for response overlap**

5 As we were interested in the electrophysiological response to the second tone of each tone-pair,
 6 we corrected for the overlap between the ERPs elicited by the first and second tone of each tone-pair
 7 stimulus. We subtracted individual-averaged single tone waveforms from each individual-averaged tone-
 8 pair waveform for each participant. The subtraction allowed us to isolate the response elicited by the
 9 second tone of each tone-pair (Clunies-Ross et al., 2015; Fox et al., 2010; Sable et al., 2004). In order to
 10 compare Ta and Tb responses across ISIs, the waveforms were then stimulus-locked such that the onset
 11 of the second tone was set to time zero, and were baseline-corrected using the 100 ms pre-stimulus
 12 interval of the corrected waveform. The waveform corrected for response overlap shall be hereafter
 13 referred to as the corrected waveform.

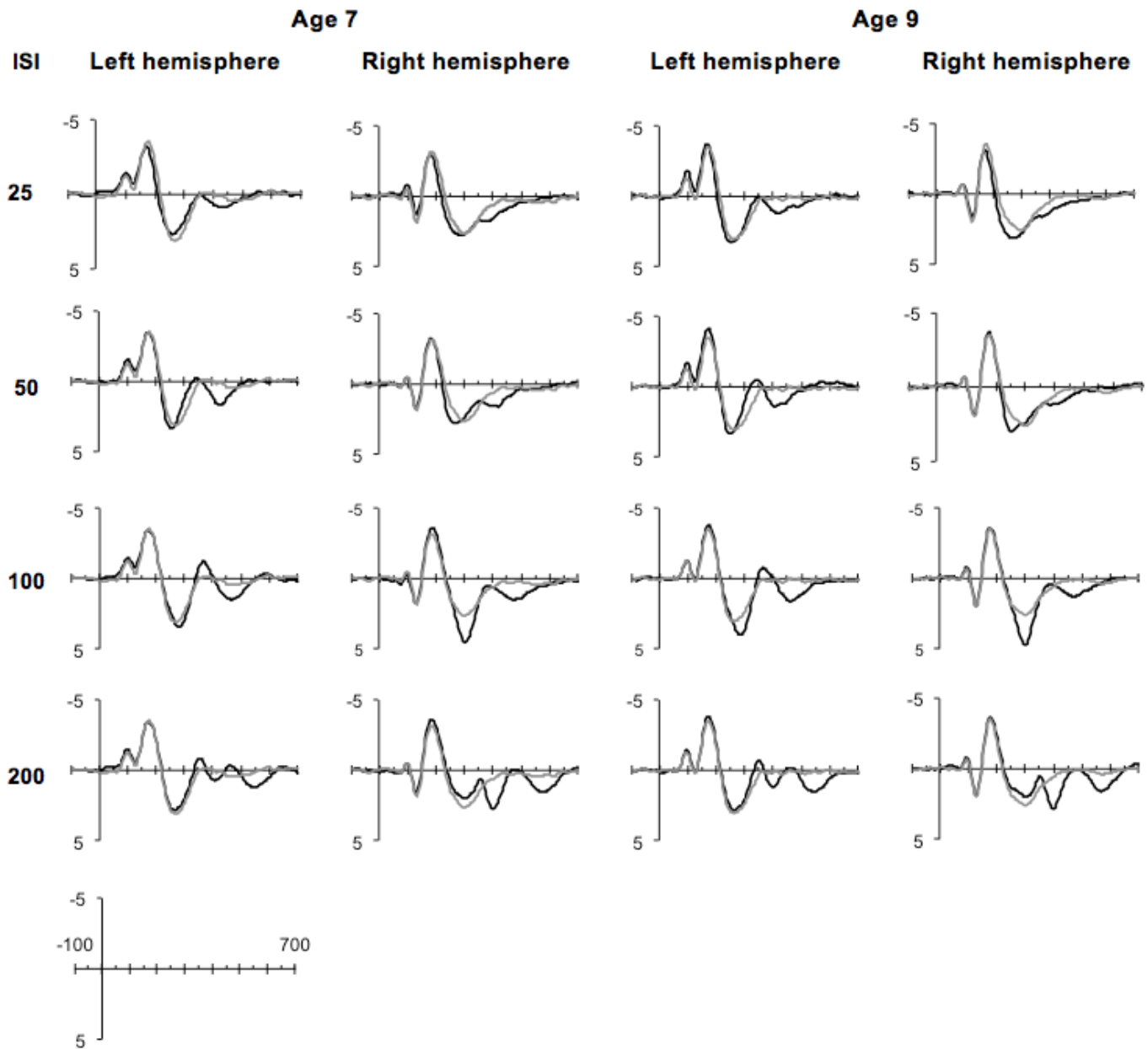
14 **2.7. Topographic distribution of ERPs**

15 The topographic distribution of the Ta and Tb of the single tone waveforms, and the corrected
 16 waveforms indicated that the Ta and Tb were largest at temporal (T7 and T8) sites. The Ta and Tb were,
 17 therefore, extracted at these sites. The grand-averaged waveforms synchronised to the onset of the first
 18 tone are presented in Figure. 1 and the grand-averaged corrected waveforms synchronised to the onset of
 19 the second tone are presented in Figure. 2. In the following sections, references to and discussions of
 20 data refer to the Ta and Tb elicited by the second tone of the tone-pairs.

21

22

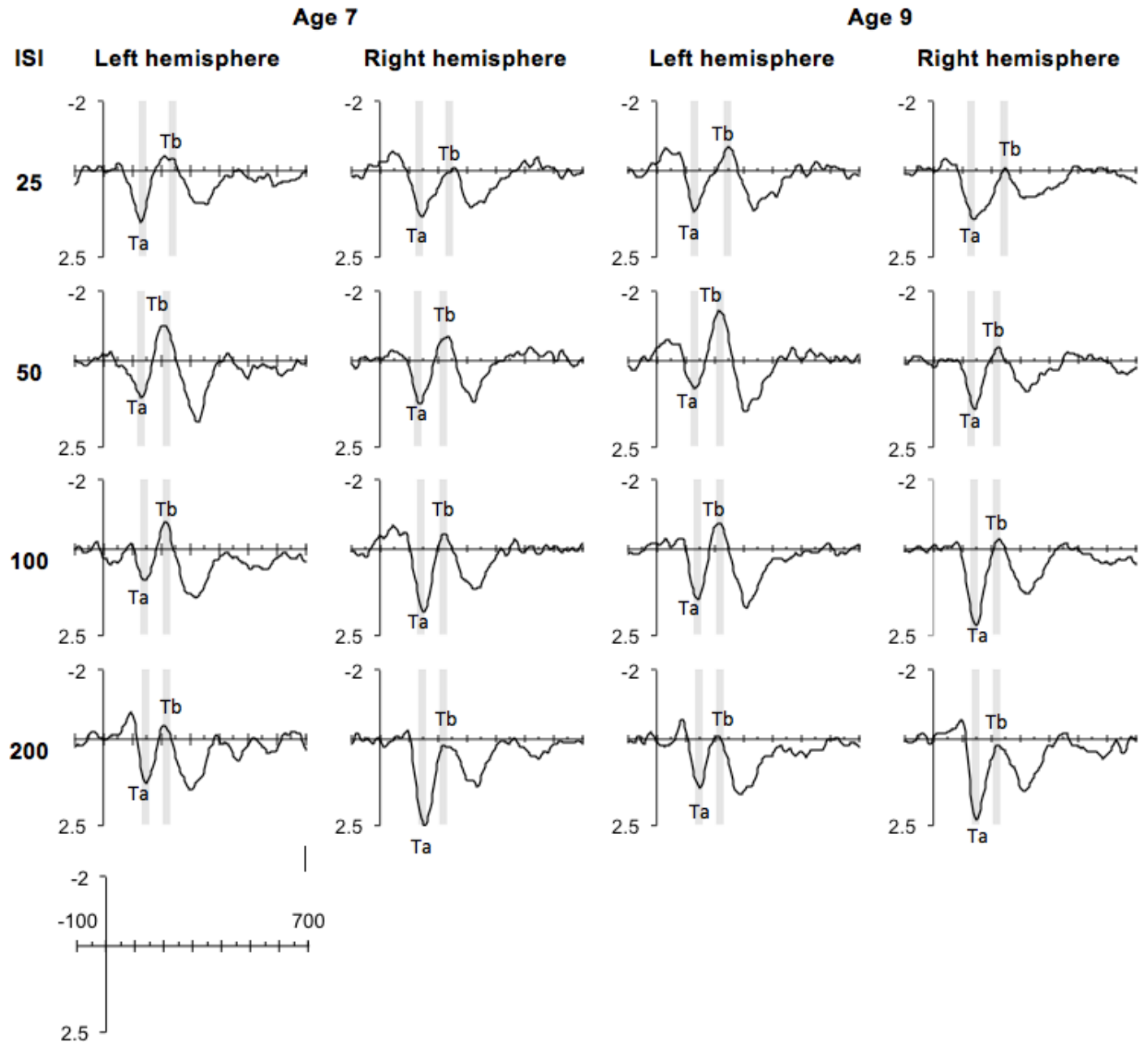
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3 *Figure 1.* Grand-averaged ERP waveforms synchronised to the onset of tone 1 of tone-pairs with ISIs of
 4 25, 50, 100 and 200 ms (black), with the single tone waveforms superimposed (grey). The amplitudes of
 5 the waveforms recorded at T7 and T8, are presented in microvolts (μV) on the y-axis, and time is
 6 presented in milliseconds (ms) on the x-axis.

7



1 *Figure 2.* Grand-averaged ERP waveforms corrected for response overlap, and synchronised to the onset
 2 of the second tone of tone-pairs. Waveforms were recorded at T7 (left hemisphere) and T8 (right
 3 hemisphere), at age 7 (left) and 9 (right). The amplitudes of the waveforms are presented in microvolts
 4 (μV) on the y-axis, and time is presented in milliseconds (ms) on the x-axis. Grey vertical bars illustrate
 5 the latency intervals used to calculate the mean amplitude for Ta and Tb.

6 **2.8. Extraction of mean amplitudes**

7 Latency windows were established for each ISI at age 7 and 9 to take into account differences in

1 the latency of the relevant peaks. Peak latencies were identified from the grand-averaged waveforms at
2 T7 and T8, and the mean amplitudes were calculated based on a 20 ms window, centred on the peak
3 latency (Clunies-Ross et al., 2015; Hakvoort et al., 2014). In Figure 2, grey vertical bars illustrate the
4 latency intervals over which the mean amplitudes were calculated. Mean amplitudes for the Tb were
5 measured relative to the mean amplitude of the previous positivity (Ta).

6 **2.9. Laterality index of rapid temporal processing**

7 One of our primary objectives was to examine the relationship between the lateralisation of rapid
8 temporal processing and phonological awareness. To do so, we calculated a laterality index (LI) using
9 Tb responses to the second tone of the 50 ms ISI tone-pairs. The Tb response was selected for analysis
10 as it has been found to reflect asymmetries in temporal processing (Clunies-Ross et al., 2015). The LI
11 was calculated as the difference between the Tb responses of the left and right hemisphere to 50 ms ISI
12 tone-pairs ($LI = \text{Left} - \text{Right}$). A negative LI indicated leftward lateralisation of the Tb response and a
13 positive LI indicated a rightward lateralisation of the Tb response. LIs were calculated for both ages.
14 (Age 7: $M = -0.09$, $SD = 2.92$, range = -7.94 to 7.46, Age 9: $M = -0.57$, $SD = 2.62$, range: -8.16 to 5.45).

15 **2.10. Data analysis**

16 All data were subject to preliminary screening measures prior to statistical analyses to ensure that
17 all the assumptions of ANOVA and regression were met. Data were winsorised to reduce the effect of
18 spurious outliers as outlined by Wilcox (2001). No more than four values were winsorised per variable.
19 Skew and kurtosis coefficients were used to assess the normality of the data. The skew and kurtosis
20 coefficients of all variables fell within the acceptable range (± 2 ; George and Mallery, 2010).
21 Multivariate outliers were screened by calculating Mahalanobis distance for each case, per analysis. No
22 multivariate outliers were detected ($p > .001$). Two repeated-measures ANOVAs were conducted. Ta and
23 Tb mean amplitudes were subject to separate $2 \times 2 \times 4$ repeated-measures ANOVAs, with age (7, 9)
24 hemisphere (left, right) and ISI (25 ms, 50 ms, 100 ms, 200 ms) treated as the within-subject variables.
25 We accounted for violations of the assumption of sphericity using the Greenhouse-Geisser correction.
26 Significance values based on the Greenhouse-Geisser correction are reported with the uncorrected
27 degrees of freedom. Regression analyses were conducted where the laterality indices (LI) (calculated for
28 the Tb response to the 50 ms ISI tone-pair at age 7 and 9) were treated as the predictors and performance

1 on the Sight Word Efficiency and Phonemic Decoding Efficiency subtests measured at age 7 and 9 were
2 treated as dependent variables.

3 **3. Results**

4 Table 3.

5 *Descriptive Statistics of the Mean Amplitudes (μV) for the Ta and Tb peaks at Age 7 and Age 9, for each*
6 *ISI and Hemisphere.*

| | | Age 7 | | Age 9 | |
|-----|--------|---------------|---------------|---------------|---------------|
| | | LH | RH | LH | RH |
| ISI | | <i>M (SD)</i> | <i>M (SD)</i> | <i>M (SD)</i> | <i>M (SD)</i> |
| Ta | 25 ms | 1.30 (1.38) | 1.22 (1.72) | 1.12 (1.31) | 1.30 (1.52) |
| | 50 ms | 0.97 (1.61) | 1.18 (1.41) | 0.77 (1.51) | 1.22 (1.32) |
| | 100 ms | 0.85 (1.60) | 1.75 (1.50) | 1.40 (1.62) | 2.13 (1.58) |
| | 200 ms | 1.27 (1.84) | 2.36 (1.41) | 1.34 (1.62) | 2.21 (1.63) |
| Tb | 25 ms | -1.60 (2.01) | -1.25 (2.22) | -1.78 (1.75) | -1.38 (2.18) |
| | 50 ms | -1.90 (2.18) | -1.81 (1.99) | -2.15 (1.90) | -1.60 (1.79) |
| | 100 ms | -1.54 (2.27) | -2.16 (2.24) | -2.09 (1.96) | -2.40 (1.75) |
| | 200 ms | -1.65 (1.95) | -2.18 (2.02) | -1.35 (1.84) | -1.94 (1.88) |

7 *Note. N = 50; LH = Left hemisphere (T7), RH = Right hemisphere (T8)*

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15 **3.1. Analysis of Variance of the Ta mean amplitudes**

1 Table 4.

2 *Analysis of Variance of Ta Mean Amplitudes with Age, Hemisphere and ISI as Within-Subject Variables.*

| Variable | <i>df</i> | <i>F</i> | ε | <i>p</i> | n_p^2 |
|------------------------|-----------|----------|---------------|----------|---------|
| age | 1, 49 | 0.40 | - | .532 | .008 |
| hemisphere | 1, 49 | 13.31 | - | .001 | .214 |
| ISI | 3,147 | 9.93 | .745 | .001 | .168 |
| age x hemisphere | 1, 49 | 0.01 | - | .921 | .000 |
| age x ISI | 3, 147 | 2.08 | .846 | .117 | .041 |
| hemisphere x ISI | 3, 147 | 5.28 | .689 | .006 | .097 |
| age x hemisphere x ISI | 3, 147 | 0.60 | .904 | .603 | .012 |

3 *Note. N = 50*

4 The interaction between hemisphere and ISI was broken down by conducting two repeated-
 5 measures ANOVAs (one for each hemisphere) with ISI as the within-subjects variable. The Ta mean
 6 amplitudes averaged across ages are presented in Figure 3. There was a significant main effect of ISI on
 7 Ta mean amplitudes measured over the right hemisphere such that Ta amplitudes increased with
 8 increasing ISI, illustrated in panel A of Figure 3. ($F(3, 147) = 16.03, p < .001, \varepsilon = .750, n_p^2 = .247$). Ta
 9 amplitudes measured over the left hemisphere did not vary significantly as a function of ISI ($F(3, 147) =$
 10 $1.54, p = .219, \varepsilon = .674, n_p^2 = .030$).

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16 **3.2 Analysis of Variance of the Tb mean amplitudes**

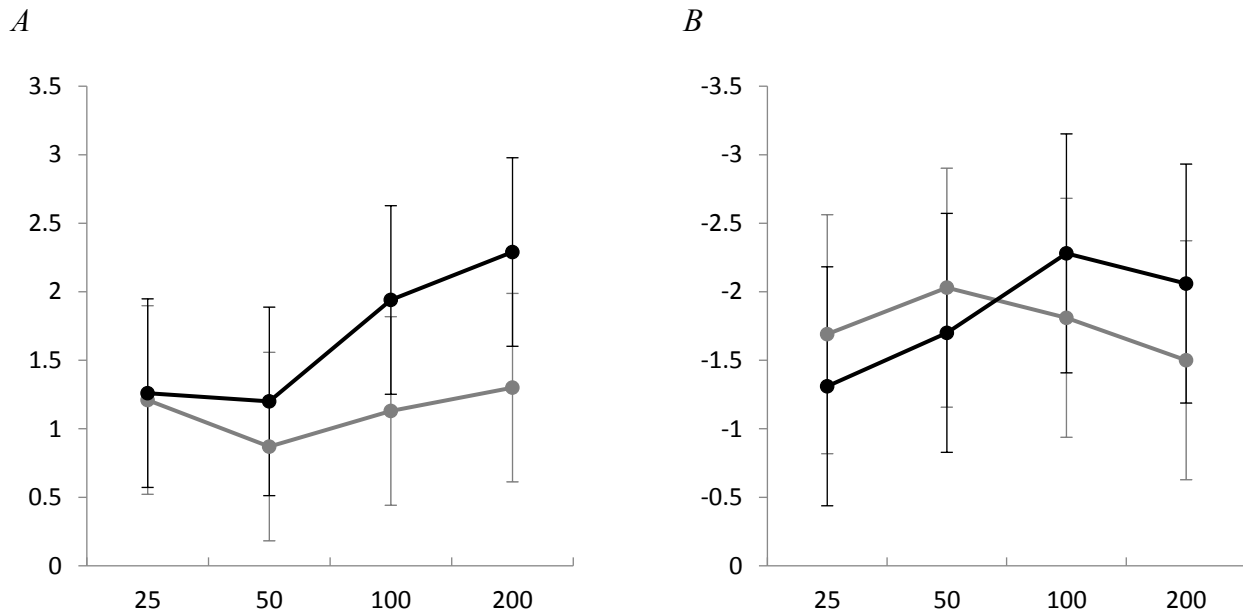
1 Table 5.

2 *Analysis of Variance of Tb Mean Amplitudes with Age, Hemisphere and ISI as Within-Subject Variables.*

| Variable | <i>df</i> | <i>F</i> | ϵ | <i>p</i> | n_p^2 |
|------------------------|-----------|----------|------------|----------|---------|
| age | 1, 49 | 0.26 | - | .612 | .005 |
| hemisphere | 1, 49 | 0.17 | - | .682 | .003 |
| ISI | 3, 147 | 2.99 | .785 | .046 | .057 |
| age x hemisphere | 1, 49 | .478 | - | .493 | .010 |
| age x ISI | 3, 147 | 1.40 | .836 | .251 | .028 |
| hemisphere x ISI | 3, 147 | 3.76 | .810 | .019 | .071 |
| age x hemisphere x ISI | 3, 147 | .260 | .871 | .828 | .005 |

3 *Note. N = 50*

4 The interaction between hemisphere and ISI was broken down by conducting two repeated-measures
 5 ANOVAs (one for each hemisphere), with ISI as the within-subjects variable. The mean Tb responses
 6 averaged across ages are presented in Figure 3. Tb responses measured over the left hemisphere were
 7 enhanced to 50 ms ISI tone-pairs (quadratic trend, $F(1, 49) = 4.06, p < .05, n_p^2 = .077$). Tb responses
 8 measured over the right hemisphere were enhanced to 100 and 200 ms ISI tone-pairs (linear trend, $F(1,$
 9 $49) = 9.48, p < .01, n_p^2 = .162$).



1 *Figure 3.* Ta (panel A) and Tb (panel B) mean amplitudes collapsed across time-points, measured over
 2 the left (grey) and right hemispheres (black) are plotted for each ISI. Amplitudes are displayed on the y-
 3 axis and are measured in microvolts (μV). The error bars reflect 95% confidence intervals for the
 4 interaction between hemisphere and ISI, for the respective component.

5 **3.3. Lateralisation of rapid temporal processing and performance on the Sight Word Efficiency** 6 **and Phonemic Decoding Efficiency subtests at age 9.**

7 *Table 6.*

8 Predictors of Sight Word Efficiency and Phonemic Decoding Efficiency at Age 9

| Outcome | Predictors | R^2 | B | $SE B$ | β | t | p |
|------------------------------|------------------|-------|--------|--------|---------|--------|------|
| Sight Word Efficiency | LI 50 ms ISI - 7 | .007 | - 0.20 | 0.34 | -.009 | - 0.60 | .550 |
| | LI 50 ms ISI - 9 | .008 | 0.23 | 0.38 | 0.09 | 0.624 | .536 |
| Phonemic Decoding | LI 50 ms ISI - 7 | .114 | - 0.98 | 0.39 | -0.34 | -2.49 | .016 |
| | LI 50 ms ISI - 9 | .002 | 0.16 | 0.47 | 0.05 | 0.34 | .738 |

9 *Note.* $N = 50$

10 The LI measured at age 7 was a significant predictor of performance on the Phonemic Decoding
 11 Efficiency subtest of the TOWRE at age 9, such that the greater the lateralisation of the Tb at age 7, the
 12 better they performed on the Phonemic Decoding Efficiency subtest 2 years later. The LI at age 9 was

1 not predictive of performance on the Phonemic Decoding Efficiency at age 9, nor were the LIs at age 7
2 and 9 predictive of performance on the Sight Word Efficiency subtest at age 9.

3 **4. Discussion**

4 The AST hypothesis states that acoustic information is processed hierarchically within the left
5 and right auditory areas of the brain, and this has been well supported by research on adult samples.
6 Current findings support the theory that neuronal ensembles in the primary auditory areas are tuned to
7 rapid temporal modulations 25-50 ms (20-40 Hz). Neuronal ensembles in the left and right secondary
8 auditory areas are differentially tuned to rapid (25-50 ms = 20-40 Hz), and slow (200-250 ms = 4-5 Hz)
9 modulations, respectively. Although the AST proposes that hemispheric asymmetries are intrinsic and
10 likely to emerge prior to adulthood, investigations in children have been sparse and inconsistent. It is
11 still unclear when these functional asymmetries appear to develop and behave in an adult-like way
12 (Telkemeyer et al., 2009). Therefore, we sought to characterise hemispheric asymmetries in rapid and
13 slow temporal processing in children at age 7 and 2 years later at age 9. Our results show that
14 hemispheric asymmetries in children at 7 - 9 years resemble that seen in young adults, suggesting that
15 hemispheric specialisation for fast and slow modulations is present at this age. We also provide evidence
16 for the relationship with hemispheric specialisation of rapid auditory processing and subsequent
17 phonemic decoding ability.

18 **4.1. Hemispheric asymmetries in Ta response**

19 We observed hemispheric asymmetries in patterns of Ta responses to rapid and slow tone-pairs.
20 There was no significant difference between Ta responses across all ISIs over the left hemisphere,
21 suggesting that the associated auditory areas in the left hemisphere may function according to a short
22 temporal integration window, and that the generator of the Ta in the left hemisphere may be mature at
23 age 7. Over the right hemisphere, Ta responses to the 25 and 50 ms ISI tone-pairs were attenuated
24 relative to Ta responses to the 100 and 200 ms ISI tone-pairs, suggesting that the generators of the Ta in
25 the right hemisphere are functioning according to a longer integration window of approximately 100 ms.
26 The longer integration window could reflect the later development of the Ta generators in the right
27 hemisphere, which is consistent with previous reports by Mahajan and McArthur (2013) who found that
28 the Ta peak over the right hemisphere continued to develop throughout adolescence, suggesting that the
29 functional development of the left and right hemispheres differs. As the reported neural generators of the

1 Ta are inconsistent, the functional implications of hemispheric asymmetries in the development of the
2 Ta require further investigation.

3 **4.2. Hemispheric asymmetries in the Tb response**

4 Previous findings in adults support a left hemisphere specialisation for rapid temporal
5 modulations and a right hemispheric specialisation for slow temporal modulations (Boemio et al., 2005;
6 Clunies-Ross et al., 2015; Jamison et al., 2006; Luo, and Poeppel, 2007; 2012). At present, our
7 understanding of when this develops during childhood is not clear (Vanvooren et al., 2014). By
8 examining the Tb responses to auditory stimuli presented with varying ISIs, we investigated whether the
9 left and right secondary auditory areas exhibit preferential processing of rapid and slow temporal
10 modulations. Based on the AST, we predicted that the left hemisphere would preferentially respond to
11 rapidly presented tones with ISIs of ~ 50 ms, whereas the right hemisphere would preferentially respond
12 to slower temporal modulations ~ 200 ms (Poeppel, 2003). Consistent with the AST, we observed the
13 preferential processing of both rapid and slow auditory stimuli over the left and right hemispheres,
14 respectively.

15 As can be seen in panel B of Figure. 3, Tb responses were largest over the left hemisphere when
16 tones were separated by 50 ms, suggesting a left hemisphere preference for rapidly presented stimuli.
17 This is consistent with the conjecture that a large proportion of neuronal populations in the left
18 secondary auditory areas are tuned to rapid temporal rates and, therefore, preferentially respond to
19 rapidly presented stimuli (Poeppel, 2003). The presence of a distinct Tb response to the 25 ms ISI tone-
20 pairs, in particular, suggests that there are neuronal ensembles in the left hemisphere capable of
21 responding to stimuli presented as quickly as 25 ms. These results provide evidence of left hemisphere
22 specialisation for rapid temporal processing in children aged 7 and 9 years, and are consistent with
23 previous findings of Thompson et al. (2016) who observed leftward lateralisation of high-frequency (20-
24 50Hz) endogenous cortical oscillations at the younger ages of 3-5 years.

25 Over the right hemisphere, Tb responses were largest for the 100 and 200 ms ISI tone-pairs,
26 indicating a preference for slower presentation rates. In Figure 1. it can be seen that over the right
27 hemisphere, at both ages 7 and 9, the Tb response to the second tone of tone pairs is not present at ISIs
28 of 25 and 50 ms, but emerges at the longer ISIs of 100 and 200 ms. The preferential processing of the
29 100 and 200 ms ISI tone-pairs in the right hemisphere is consistent with previous findings of right

1 hemisphere preference for the processing of slowly unfolding auditory stimuli (Abrams et al., 2008;
2 Clunies-Ross et al., 2015; Luo and Poeppel, 2007; 2012). Interestingly, the Tb response to the 100 ms
3 ISI tone-pairs over the right hemisphere was as large as that of the 200 ms ISI tone-pairs, despite
4 representing a much faster modulation rate than the frequently discussed 200-250 ms. This finding
5 suggests that finer tuning of neuronal ensembles in the right secondary auditory areas may occur beyond
6 the age of 9.

7 The same pattern of hemispheric asymmetries was observed at age 7 as at age 9, suggesting that
8 neuronal tuning to specific modulations did not change significantly over this time. This was particularly
9 unexpected given that studies have demonstrated marked development in the Ta and Tb over this
10 developmental period (Bishop et al., 2011; Tonnquist-Uhlen et al., 2003). However, this may suggest
11 that there are differences between the maturation rates of Ta and Tb neural generators, and the
12 maturation of their functional properties. Nevertheless, our results clearly demonstrate that hemispheric
13 preferences for fast and slow modulations are present in children at age 7 and 9. In the context of
14 previous findings by Thompson et al (2016) and Vanvooren et al (2014), our results suggest that
15 temporal processing asymmetries may become more consistent from at least 7 years. Earlier
16 inconsistencies across studies of younger children may reflect reduced prominence of functional
17 asymmetries, and therefore, difficulty identifying such asymmetries consistently.

18 Similar to the current study, Clunies-Ross et al. (2015) conducted an experiment with young
19 adults, which examined Tb responses to tone-pairs separated by ISIs of 50 and 200 ms. They found that
20 Tb responses to the second tone of the 50 ms ISI tone-pairs were enhanced over the left hemisphere
21 relative to the right hemisphere ($d = 0.45$), providing evidence for a left hemisphere advantage for
22 rapidly presented tones. In the present study, the left hemisphere advantage for rapidly presented tones
23 was not found to be as prominent in children ($d = 0.16$) as was found in young adults, suggesting that
24 although the hemispheric asymmetries are present at age 7 and remain stable until age 9, further tuning
25 of the neuronal populations in the right hemisphere may occur between childhood and young adulthood.

26 **4.3 Rapid temporal processing: left-hemisphere vs. bilateral**

27 Together, functional asymmetries in the processing of tone-pairs with short and long ISIs provide
28 evidence for a left hemisphere preference for the processing of rapidly presented stimuli and a right
29 hemisphere preference for slowly presented stimuli. Previous research investigating asymmetries in

1 temporal processing have drawn inconsistent conclusions as to whether neuronal ensembles functioning
2 according to a short temporal integration window are distributed bilaterally or primarily in the left
3 hemisphere. Some researchers have observed bilateral rapid temporal processing (Boemio et al., 2005;
4 Luo and Poeppel, 2012), whilst others have demonstrated a left hemisphere advantage (Okamoto et al.,
5 2009; Zaehle et al., 2004). Vanvooren et al. (2014) proposed that the inconsistency in reports of
6 asymmetries in rapid temporal processing might be due to the differences in methodology and the type
7 of neuroimaging techniques used. Our current findings and the findings of previous research (Clunies-
8 Ross et al., 2015) demonstrate how the Ta and Tb can be used to differentiate between auditory areas in
9 which rapid temporal processing occurs bilaterally and those in which it occurs primarily in the left-
10 hemisphere. The present data do not provide evidence for bilateral rapid auditory processing in primary
11 auditory areas as proposed by Poeppel (2003) in the AST, potentially due to the slower development of
12 right hemisphere neural generators (Mahajan and McArthur, 2013). However, our results support a left
13 hemisphere preference for the processing of rapidly presented stimuli, and, consistent with the AST, the
14 observed asymmetry was reflected by the Tb of the T-complex, which is proposed to originate from the
15 secondary auditory areas (Tonnquist-Uhlen et al., 2003).

16 **4.4. Hemispheric asymmetries in rapid temporal processing at age 7 predict phonemic decoding at** 17 **age 9.**

18 Our results suggest that children who showed greater leftward lateralisation of rapid temporal
19 processing at age 7 performed better on the Phonemic Decoding Efficiency subtest 2 years later. The LI
20 at age 7 accounted for 11.4 % of variance in Phonemic Decoding Efficiency performance at age 9,
21 demonstrating that greater leftward hemispheric specialisation for rapid temporal processing may
22 contribute to subsequent phonemic decoding ability (Fox et al., 2012; Tallal, 2004; Tallal et al., 1993;
23 Tallal and Gaab, 2006). This suggests that perhaps one must be able to differentiate phonological sounds
24 before being able to form mental representations of the sounds (Tallal, 1980; Tallal et al., 1993), map
25 them onto letters, and be able to use their knowledge of grapheme to phoneme associations to decode
26 and accurately read aloud written words. Further evidence in support of this idea comes from the lack of
27 association between the LI at age 9 and Phonemic Decoding Efficiency at age 9. In sum, lateralisation of
28 rapid temporal processing at age 7, as indexed by the Tb, appears to be a moderate predictor of future
29 phonemic decoding ability, rather than current phonemic decoding ability. As expected, LIs measured at
30 age 7 and 9 did not predict sight word reading ability at age 9. Our findings are consistent with the

1 notion that sight word reading ability is more dependent on familiarity with real words, than
2 phonological ability (Espy et al., 2004). This adds further support for the contribution of rapid temporal
3 processing to performance on tasks that accessing phonological representations.

4 One of the key ideas in the literature pertaining to hemispheric specialisation is that greater
5 lateralisation or specialisation of a particular function or process allows for better efficiency, and in turn,
6 better performance. Our findings suggest that left hemisphere specialisation of rapid temporal processing
7 is associated with better outcomes on tests of phonemic decoding ability, and further suggest that this
8 lateralisation may be a precursor for the future development of more complex linguistic skills. It builds
9 on previous research by Fox et al. (2012), by demonstrating the relationship between the leftward
10 lateralisation of rapid temporal processing and subsequent phonemic decoding of written language, in
11 addition to repeating nonwords.

12 **4.5. Conclusion**

13 In the present study, we provide evidence of functional asymmetries in temporal processing in
14 children at age 7 and 9. Tb responses to the second tone of a tone-pair stimulus were largest when
15 separated by 50 ms in the left hemisphere, and 100-200 ms in the right hemisphere. Our findings suggest
16 that neuronal populations in the left secondary auditory cortex preferentially respond to rapidly
17 presented stimuli and neuronal populations in the right secondary auditory cortex preferentially respond
18 to slowly presented stimuli, consistent with the predictions of the AST hypothesis (Poeppel, 2003).
19 Although the pattern of asymmetry did not change over the 2 year period investigated in the present
20 study, we suggest that asymmetries may further mature after the age of 9, as left-hemisphere advantage
21 for rapid temporal processing was not as prominent as has been seen in adults (Clunies-Ross et al., 2015)
22 and right hemisphere advantage did not appear as finely tuned to ~200 ms stimuli as observed in adults.

23 Our results demonstrate auditory stimuli presented as quickly as 25 ms are discriminable in the
24 auditory ERP of children as young as 7. The lateralisation of an individual's Tb response to the 50 ms
25 ISI tone-pair at age 7 was a significant predictor of phonemic decoding ability two years later,
26 suggesting that hemispheric specialisation of rapid temporal processing may be a precursor to
27 subsequent phonemic decoding ability. Finally, our findings provide support for previous suggestions
28 that the Tb may be an important ERP for the investigation of the relationship between auditory
29 processing and complex language abilities.

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References

- 1
2 Abrams, D.A., Nicol, T., Zecker, S., Kraus, N., 2008. Right-hemisphere auditory cortex is dominant for
3 coding syllable speech patterns in speech. *J. Neurosci.* 28, 3958–3965.
4 doi:<http://dx.doi.org/10.1523/JNEUROSCI.0187-08.2008>
- 5 Albrecht, R., Suchodoletz, W. v, Uwer, R., 2000. The development of auditory evoked dipole source
6 activity from childhood to adulthood. *Clin. Neurophysiol.* 111, 2268–2276.
- 7 Bishop, D.V.M., Anderson, M., Reid, C., Fox, A.M., 2011. Auditory development between 7 and 11
8 years: an event-related potential (ERP) study. *PLoS One* 6, e18993.
9 doi:<http://dx.doi.org/10.1371/journal.pone.0018993>
- 10 Boemio, A., Fromm, S., Braun, A., Poeppel, D., 2005. Hierarchical and asymmetric temporal sensitivity
11 in human auditory cortices. *Nat. Neurosci.* 8, 389–95. doi:[10.1038/nn1409](https://doi.org/10.1038/nn1409)
- 12 Clunies-Ross, K.L., Brydges, C.R., Nguyen, A.T., Fox, A.M., 2015. Hemispheric asymmetries in
13 auditory temporal integration: a study of event-related potentials. *Neuropsychologia* 68, 201–208.
14 doi:[10.1016/j.neuropsychologia.2015.01.018](https://doi.org/10.1016/j.neuropsychologia.2015.01.018)
- 15 Fox, A.M., Anderson, M., Reid, C., Smith, T., Bishop, D.V.M., 2010. Maturation of auditory temporal
16 integration and inhibition assessed with event-related potentials (ERPs). *BMC Neurosci.* 11, 49.
17 doi:[10.1186/1471-2202-11-49](https://doi.org/10.1186/1471-2202-11-49)
- 18 Fox, A.M., Reid, C.L., Anderson, M., Richardson, C., Bishop, D.V.M., 2012. Maturation of rapid
19 auditory temporal processing and subsequent nonword repetition performance in children. *Dev. Sci.*
20 15, 204–211.
- 21 George, D., Mallery, P., 2010. *SPSS for Windows Step by Step: A Simple Guide and Reference 17.0*
22 *Update*, 10th ed. Pearson, Boston, Mass.
- 23 Giraud, A.-L., Kleinschmidt, A., Poeppel, D., Lund, T.E., Frackowiak, R.S.J., Laufs, H., 2007.
24 Endogenous cortical rhythms determine cerebral specialization for speech perception and
25 production. *Neuron* 56, 1127–34. doi:[10.1016/j.neuron.2007.09.038](https://doi.org/10.1016/j.neuron.2007.09.038)
- 26 Goswami, U., 2011. A temporal sampling framework for developmental dyslexia. *Trends Cogn. Sci.* 15,
27 3–10. doi:<http://dx.doi.org/10.1016/j.tics.2010.10.001>
- 28 Hakvoort, B., van der Leij, A., Maurits, N., Maassen, B., van Zuijlen, T.L., 2014. Basic auditory
29 processing is related to familial risk, not to reading fluency: An ERP study. *Cortex.* 63C, 90–103.
30 doi:[10.1016/j.cortex.2014.08.013](https://doi.org/10.1016/j.cortex.2014.08.013)
- 31 Irimia, A., Van Horn, J.D., Halgren, E., 2012. Source cancellation profiles of electroencephalography
32 and magnetoencephalography. *Neuroimage* 59, 2464–2474. doi:[10.1016/j.neuroimage.2011.08.104](https://doi.org/10.1016/j.neuroimage.2011.08.104)
- 33 Jamison, H.L., Watkins, K.E., Bishop, D.V.M., Matthews, P.M., 2006. Hemispheric specialization for
34 processing auditory nonspeech stimuli. *Cereb. Cortex* 16, 1266–75. doi:[10.1093/cercor/bhj068](https://doi.org/10.1093/cercor/bhj068)
- 35 Lang, A.H., Eerola, O., Korpilahti, P., Holopainen, I., Salo, S., Aaltonen, O., 1995. Practical issues in
36 the clinical application of mismatch negativity. *Ear Hear.* 16, 118–130.
- 37 Luo, H., Poeppel, D., 2012. Cortical oscillations in auditory perception and speech: evidence for two

- 1 temporal windows in human auditory cortex. *Front. Psychol.* 3, 1–10.
2 doi:<http://dx.doi.org/10.3389/fpsyg.2012.00170>
- 3 Luo, H., Poeppel, D., 2007. Phase patterns of neuronal responses reliably discriminate speech in human
4 auditory cortex. *Neuron* 54, 1001–1010. doi:<http://dx.doi.org/10.1016/j.neuron.2007.06.004>
- 5 Mahajan, Y., McArthur, G., 2013. Maturation of the auditory t-complex brain response across
6 adolescence. *Int. J. Dev. Neurosci.* 31, 1–10. doi:[10.1016/j.ijdevneu.2012.10.002](http://dx.doi.org/10.1016/j.ijdevneu.2012.10.002)
- 7 Marinus, E., Kohnen, S., McArthur, G., 2013. Australian comparison data for the Test of Word Reading
8 Efficiency (TOWRE). *Aust. J. Learn. Difficulties* 18, 199–212.
9 doi:[10.1080/19404158.2013.852981](http://dx.doi.org/10.1080/19404158.2013.852981)
- 10 McArthur, G., Bishop, D.V.M., Proudfoot, M., 2003. Do video sounds interfere with auditory event-
11 related potentials. *Behav. Res. Methods, Instruments, Comput.* 35, 329–333.
12 doi:<http://dx.doi.org/10.3758/BF03202561>
- 13 Naatanen, R., 1995. The mismatch negativity: a powerful tool for cognitive neuroscience. *Ear Hear.* 16,
14 6–18.
- 15 Okamoto, H., Stracke, H., Draganova, R., Pantev, C., 2009. Hemispheric asymmetry of auditory evoked
16 fields elicited by spectral versus temporal stimulus change. *Cereb. Cortex* 19, 2290–7.
17 doi:[10.1093/cercor/bhn245](http://dx.doi.org/10.1093/cercor/bhn245)
- 18 Poeppel, D., 2003. The analysis of speech in different temporal integration windows: cerebral
19 lateralization as “asymmetric sampling in time.” *Speech Commun.* 41, 245–255.
20 doi:[10.1016/S0167-6393\(02\)00107-3](http://dx.doi.org/10.1016/S0167-6393(02)00107-3)
- 21 Ponton, C., Eggermont, J.J., Khosla, D., Kwong, B., Don, M., 2002. Maturation of human central
22 auditory system activity: Separating auditory evoked potentials by dipole source modeling. *Clin.*
23 *Neurophysiol.* 113, 407–420.
- 24 Ruhnau, P., Herrmann, B., Maess, B., Schröger, E., 2011. Maturation of obligatory auditory responses
25 and their neural sources: evidence from EEG and MEG. *Neuroimage* 58, 630–9.
26 doi:[10.1016/j.neuroimage.2011.06.050](http://dx.doi.org/10.1016/j.neuroimage.2011.06.050)
- 27 Sable, J.J., Low, K.A., Maclin, E.L., Fabiani, M., Gratton, G., 2004. Latent inhibition mediates N1
28 attenuation to repeating sounds. *Psychophysiology* 41, 636–642.
29 doi:<http://dx.doi.org/10.1111/j.1469-8986.2004.00192.x>
- 30 Semlitsch, H. V, Anderer, P., Schuster, P., Presslich, O., 1986. A solution for reliable and valid
31 reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology* 23, 695–703.
32 doi:<http://dx.doi.org/10.1111/j.1469-8986.1986.tb00696.x>
- 33 Shafer, V.L., Schwartz, R.G., Martin, B., 2011. Evidence of deficient central speech processing in
34 children with specific language impairment: the T-complex. *Clin. Neurophysiol.* 122, 1137–55.
35 doi:[10.1016/j.clinph.2010.10.046](http://dx.doi.org/10.1016/j.clinph.2010.10.046)
- 36 Shafer, V.L., Yu, Y.H., Wagner, M., 2015. Maturation of cortical auditory evoked potentials (CAEPs) to
37 speech recorded from frontocentral and temporal sites: Three months to eight years of age. *Int. J.*
38 *Psychophysiol.* 95, 77–93. doi:[10.1016/j.ijpsycho.2014.08.1390](http://dx.doi.org/10.1016/j.ijpsycho.2014.08.1390)
- 39 Tanna, N., 2009. Test review: Word-reading efficiency. *J. Occup. Psychol.* 11, 45–48.

- 1 Telkemeyer, S., Rossi, S., Koch, S.P., Nierhaus, T., Steinbrink, J., Poeppel, D., Obrig, H., Wartenburger,
2 I., 2009. Sensitivity of newborn auditory cortex to the temporal structure of sounds. *J. Neurosci.* 29,
3 14726–33. doi:10.1523/JNEUROSCI.1246-09.2009
- 4 Thompson, E.C., Woodruff Carr, K., White-Schwoch, T., Tierney, A., Nicol, T., Kraus, N., 2016.
5 Hemispheric Asymmetry of Endogenous Neural Oscillations in Young Children: Implications for
6 Hearing Speech In Noise. *Sci. Rep.* 6, 19737. doi:10.1038/srep19737
- 7 Tonnquist-Uhlen, I., Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2003. Maturation of human
8 central auditory system activity: the T-complex. *Clin. Neurophysiol.* 114, 685–701.
9 doi:10.1016/S1388-2457(03)00005-1
- 10 Tonnquist-Uhlen, I., Ponton, C.W., Eggermont, J.J., Kwong, B., Don, M., 2003. Maturation of human
11 central auditory system activity: the T-complex. *Clin. Neurophysiol.* 114, 685–701.
12 doi:http://dx.doi.org/10.1016/S1388-2457(03)00005-1
- 13 Torgeson, J.K., Wagner, R.K., Rashotte, C.A., 1999. Test of word reading efficiency. ProEd, Austin,
14 TX.
- 15 Vandewalle, E., Boets, B., Ghesquière, P., Zink, I., 2012. Auditory processing and speech perception in
16 children with specific language impairment: Relations with oral language and literacy skills. *Res.*
17 *Dev. Disabil.* 33, 635–644. doi:10.1016/j.ridd.2011.11.005
- 18 Vanvooren, S., Poelmans, H., Hofmann, M., Ghesquiere, P., Wouters, J., Ghesquière, P., Wouters, J.,
19 2014. Hemispheric Asymmetry in Auditory Processing of Speech Envelope Modulations in
20 Prereading Children. *J. Neurosci.* 34, 1523–9. doi:10.1523/JNEUROSCI.3209-13.2014
- 21 Wagner, M., Shafer, V.L., Haxhari, E., Kiproviski, K., Behrmann, K., Griffiths, T., 2017. Stability of the
22 Cortical Sensory Waveforms, the P1-N1-P2 Complex and T-Complex, of Auditory Evoked
23 Potentials. *J. Speech, Lang. Hear. Res.* 60, 2105–2116.
- 24 Wagner, M., Shafer, V.L., Martin, B., Steinschneider, M., 2013. The effect of native-language
25 experience on the sensory-obligatory components, the P1-N1-P2 and the T-complex. *Brain Res.*
26 1522, 31–37. doi:10.1016/j.brainres.2013.04.045
- 27 Wolf, M., Vellutino, F. and Berko Gleason, J. 1998: A psycholinguistic account of reading. In Berko
28 Gleason, J. and Bernstein Ratner, N., editors, *Psycholinguistics* (2nd edn) Fort Worth, TX:
29 Harcourt Brace College Publishers, pp. 409–451
- 30 Woldorff, M.G., 1993. Distortion of ERP averages due to overlap from temporally adjacent ERPs:
31 Analysis and correction. *Psychophysiology* 30, 98–119.
- 32 Wolpaw, J.R., Penry, J.K., 1975. A temporal component of the auditory evoked response.
33 *Electroencephalogr. Clin. Neurophysiol.* 39, 609–620. doi:http://dx.doi.org/10.1016/0013-
34 4694(75)90073-5
- 35 Zaehle, T., Wüstenberg, T., Meyer, M., Jäncke, L., 2004. Evidence for rapid auditory perception as the
36 foundation of speech processing: a sparse temporal sampling fMRI study. *Eur. J. Neurosci.* 20,
37 2447–56. doi:10.1111/j.1460-9568.2004.03687.x