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Measurement of temporal-order judgment in children

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Abstract. Abnormal auditory temporal processing might be an underlying deficit in language disabilities. The auditory temporal-order threshold, one measure for temporal processing abilities, is defined as the shortest time interval between two acoustic events necessary for a person to be able to identify the correct temporal order. In our study, we examined the reliability of the auditory temporal-order threshold during a one-week period and over a time interval of four months in normally developing children aged 5 to 11 years. The results of our method show that children younger than 7 years have difficulties performing the task successfully. The reliability of the assessment of the temporal-order threshold during a period of one week is only moderate, and its stability over a time interval of four months is low. The results show that auditory-order thresholds in children have to be treated with caution. A high temporal-order threshold does not necessarily predict disabilities in temporal processing.

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INTRODUCTION

A popular hypothesis in clinical neuropsychology is that impaired auditory perception constitutes the underlying basis of learning problems, including specific reading and language disabilities (Katz and Wilde 1985). One of the characteristic symptoms of central auditory-processing disorders is auditory temporal-processing deficits (American Speech-Language-Hearing Association 1996). Over the last forty years, evidence has accumulated supporting the assumption that a deficit in temporal processing might underlie certain language disabilities (Wittmann 1999). Numerous investigations indicate that temporal-processing deficits and language impairments are associated in children and adults with dyslexia (Hari et al. 1999, Heath et al. 1999, Tallal 1980, Watson 1992), children with specific language impairments (Fitch et al. 1997, Tallal and Piercy 1973, Wright et al. 1997), and patients with damage to the left cerebral hemisphere with aphasia (Efron 1963, von Steinbüchel et al. 1999, Swisher and Hirsh 1972). This assumption is, however, controversial (Bishop et al. 1999, Mody et al. 1997, Nittrouer 1999, Wittmann and Fink 2004). Despite contradictory findings, therapeutic applications of testing auditory temporal processing have been designed during the past few years. Feedback training has been employed to train temporal-processing abilities of two stimuli in children with language-learning impairments (Merzenich et al. 1996, Tallal et al. 1996) and in adults with aphasia (von Steinbüchel 1995, 1996).

The functional link between the basic deficit in the perception of temporal order and language impairments is thought to occur at the phonemic level. The temporal order of certain spectral components that are tens of milliseconds apart have to be detected for the discrimination of stop consonants (Miller 1990, Tallal et al. 1996). If there is a general deficit in the detection of the temporal order of rapidly-presented stimuli, specific problems can occur in detecting the temporal order of spectral features, thereby impairing the perception of stop consonants. Many studies indicate such deficits in phoneme perception in children with specific language impairment or dyslexia (Godfrey et al. 1981, Liberman et al. 1974, Manis et al. 1997, Mody et al. 1997).

Subjects' abilities to identify the temporal order of two stimuli can be assessed by measuring the temporal-order threshold (OT), which is defined as the minimum interval between two stimuli at which the correct sequence is recognizable. There are several main factors that characterize the auditory OT task, including: (i) the signal quality (tones or clicks); (ii) stimulation mode (intra-hemispheric or inter-hemispheric, see below); and (iii) the algorithm of stimulus presentation. The employment of different stimuli and different classic and adaptive algorithms influences the absolute values of order thresholds that are measured (e.g., Lotze et al. 1999, Meister et al. 1998, Shelton et al. 1982). In general, adaptive algorithms are more efficient than classic methods for measuring the OT (Treutwein 1995). In adaptive procedures, the stimuli presented depend on subjects' previous responses. Therefore, fewer trials are required to estimate the OT. Especially in children, adaptive methods seem to be more effective than classic methods, like the constant-step method. Cacace et al. (2000) determined the OT of four reading-impaired children and four age-matched controls by using an adaptive-staircase method and a constant-step algorithm. The unimpaired children had no problems with the constant or the adaptive method. In contrast, the children with reading impairments had great difficulties with the constant-step method. The authors concluded that the constant-step method is more difficult than adaptive methods, as it requires more cognitive resources, such as attention and flexibility.

Although the absolute threshold values depend on the stimulation modes used, the results are often comparable. Swisher and Hirsh (1972) found that patients with left-hemispheric brain lesions and aphasia have increased OTs, regardless of the stimuli employed (tones or clicks) and stimulation modes. In an inter-hemispheric condition, one acoustic signal is presented to the right and the other to the left ear with an inter-stimulus interval in between; in an intra-hemispheric condition, a sound is presented to both ears, followed by a second sound with a certain inter-stimulus interval.

Despite the use of various OT measures in basic research and clinical settings, studies rarely report measures of reliability. Meister et al. (1998) tested young adults twelve times using three different adaptive procedures. Intra-individual standard deviations of each method were 4 to 5 times smaller than the inter-individual standard deviations. Steinbüchel et al. (1999) assessed the auditory OT three times in subjects with aphasic syndromes and in other patient groups with lesions in areas not primarily associated with language functions. The OT was measured on three consecutive days. The within-subject factor "day" showed no significant effect. No reliability values, however, were indicated. To sum up, the current database on the test-retest reliability of auditory OT is quite small and only has values for adults. Very little is known about the test-retest reliability of the auditory OT in children.

To assess the OT in children with language impairments, not only the reliability of measurement but also the development of temporal-processing abilities in normally developing children has to be known. Results of several investigations indicate that the OT decreases with age. Nickisch (1999) measured the auditory OT in 5- to 9-year-old children and found that OT improved with age. However, a large standard deviation occurred in all age groups. Kegel et al. (1988) tested the ability of 40 language-impaired and 40 control children to detect the temporal order of two tones. Each of the two groups consisted of 20 pre-school children and 20 school-age children. The results indicated that the temporal-order thresholds of younger children were significantly higher than those of the older children. The thresholds of the language-impaired subjects were higher than those of the controls. Veit (unpublished results) reported the results of a longitudinal study in which auditory OT was assessed in seven language-impaired children and five controls twice a year over a period of three years. The experiments showed that the OTs of language-impaired children were higher than those of controls. Over the years, the OTs of all children decreased significantly. However, the results showed high inter-subject, as well as intra-subject, variability. In these studies, the authors did not report whether all young children participated in the examination successfully. It is still not known at which age normally developing children are capable of understanding the instructions and can finish the test.

We examined children aged 5 to 11 years to estimate the accuracy and reliability of the OT assessment in young children. We used an auditory-stimulation paradigm to test the OTs. An auditory paradigm was chosen because there is more evidence for a deficit in temporal-order judgments in the auditory domain and conflicting evidence for such a deficit in the visual domain (see Farmer and Klein 1995). We chose an inter-hemispheric presentation mode with two clicks, one click presented to each ear. This test paradigm, enabling extremely short stimuli to be used, has been applied in basic research (Jaskowski 1993, Mills and Rollman 1980) and in clinical studies. These included adults with damage to the left cerebral hemisphere and aphasia (von Steinbüchel et al. 1999), as well as children with specific language impairments (Kegel et al. 1988, Landauer, unpublished results, Nickisch 1999). The following questions were addressed in our study: (i) at which age can children be tested with the OT task (feasibility); (ii) are there age-related changes in the auditory OT; (iii) what is the test-retest reliability of the OT after a short period of one week (reliability); (iv) are there fluctuations in OTs over a longer time interval of four months (stability)?

METHODS

Subjects

One hundred and eight monolingual German-speaking children between the ages of 5 and 11 years (46 girls and 62 boys) were tested in this study (Table I). They were contacted through local schools and kindergartens. All parents were interviewed to ensure that the children had obtained a normal education, had no obvious language-development problems, and exhibited no emotional or behavioral disorders. All subjects had a normal hearing status. Informed consent was provided by the parents of each child.

Measures

HEARING STATUS

The hearing status was screened with a pure-tone audiometric screening test at 250 Hz, 1 000 Hz, and 6 000

Table I

Demographic variables of participants and feasibility of the auditory temporal-order threshold task over the age groups.

Age (years)	Gender (male/female)	Total (*n*)	Completion of test *n* (%)
5	9/2	11	7 (64)
6	3/5	8	5 (63)
7	7/9	16	15 (94)
8	15/9	24	20 (83)
9	17/11	28	28 (100)
10	7/7	14	14 (100)
11	4/3	7	7 (100)
	62/46	108	96 (89)

Hz. The left and right ears were examined separately. Children with a hearing level above 20 dB were excluded.

AUDITORY TEMPORAL-ORDER THRESHOLD (OT)

The experimental design in our study consisted of repetitive temporal-order discrimination trials. One trial involved the presentation of a stimulus pair in which the two stimuli were separated by a controlled inter-stimulus interval (ISI). One stimulus of the pair was presented to the right ear and the other to the left ear. The children were requested to indicate in which ear the first of the two clicks was heard.

The stimuli were pairs of clicks with a duration of 1 ms and a variable inter-stimulus interval. The clicks were generated by an IBM-PC compatible computer (AM 486DX/ 100 MHz) with a standard I/O and an AD/DA extension card and connected to a standard acoustical amplifier (Kenwood KA 1080). The clicks were rectangular electrical pulses with an amplitude of 5 V and were presented *via* headphones with 100 dB SPL. Our subjects described the loudness of the stimuli as pleasant and not too loud.

The adaptive algorithm YAAP (Yet Another Adaptive Procedure) (Treutwein 1997) was used for stimulus presentation and computation of the OT. YAAP is an implementation of an adaptive psychophysical method based on Bayesian statistics to estimate the threshold of a psychometric function. The basic idea behind this method is that most information about the location of a threshold is obtained by presenting the next stimulus trial at the current best estimate of the threshold. The ISI of each trial is determined by a Bayesian estimator for the threshold, which provides the best estimate of the threshold (maximum-likelihood). During an initial phase, ten trials are performed to obtain preliminary data for the likelihood information. This initial phase of ten presentations consists of a simple up-down staircase method covering the range of ISI from 80% of a specified upper limit (600 ms) to a lower limit (10 ms) in equal steps of 20%. The order of stimulus presentation (left first vs. right first) is randomly selected. In the final phase, where the ISIs presented are based on the estimation process, the threshold is reached when a stop criterion has been fulfilled. This stop criterion corresponds to a 75%-probability level of detection with a 95% confidence interval of ± 10 ms around the estimated threshold (for details see Mates et al. 2001). Two measures can be analyzed: the temporal-order threshold and the number of trials that are necessary to reach the stop criterion (a measure for the consistency of the subject's answers). Measurements with the maximum-likelihood algorithms have proven to measure: (i) with comparably low intra-individual variability; and (ii) with shorter test duration than other methods (Shelton et al. 1982). The YAAP procedure is also sensitive for assessing OT in patients with aphasia (von Steinbüchel et al. 1999) and children with dyslexia (Landauer, unpublished results).

Procedure

All tests were conducted in a quiet testing room. To motivate the participants, the OT task was embedded in a background story about air-traffic controlling and lasted approximately 15 to 20 min. Participants were tested individually while seated opposite the examiner who sat in front of the computer screen. Subjects were instructed to indicate the temporal order of the two clicks by pointing to the ear in which they had heard the first one. They were advised to point to both ears only when they had the clear impression of simultaneity. All participants received a short introductory session in which they were presented with pairs of clicks with a long ISI of 600 ms. Subjects had to identify the correct order of three consecutive trials with ISIs of 600 ms. If they were not able to identify the correct temporal order in all three trails, we repeated the test instruction. If a subject still had problems identifying the correct temporal order of at least one of the trials with an ISI of 600 ms, we assumed s/he did not understand the task, and the session was finished. Formal testing followed this short introductory session. Ninety-six of the 108 children were tested successfully. To evaluate the test-retest reliability and stability of performance, 54 children were tested twice. Twenty subjects (10 boys and 10 girls, mean age = 7 years 11 months) participated again after 1 week, and another 35 children (22 boys, 13 girls, mean age = 7 years 10 months) participated again after 4 months.

RESULTS

Feasibility

Approximately 60% of the 5- and 6-year-old children were able to complete the test successfully. At the ages of 7 and 8 years, more than 80% of the subjects, and between the ages of 9 and 11, 100% of the subjects were able to perform the test (Table I).

Table II

Auditory temporal-order threshold (OT) values and number of trials in one session of measurement

Age (years)	*n*	OT (ms) mean ± SD	number of trials mean ± SD
5	7	132 ± 37	92 ± 24
6	5	98 ± 20	87 ± 47
7	15	90 ± 30	83 ± 30
8	20	82 ± 38	67 ± 19
9	28	74 ± 35	68 ± 25
10	14	68 ± 27	61 ± 18
11	7	71 ± 40	80 ± 36

Values represent means and standard deviations (SD) for different age groups.

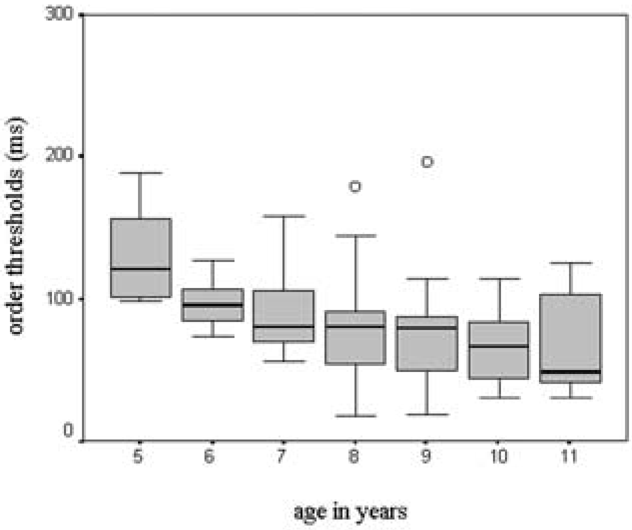

Fig. 1. The effect of age on the temporal-order threshold. The boxplot displays the median (horizontal line inside the box), the 25th percentile (lower boundary of the box), the 75th percentile (upper boundary of the box), the smallest and the largest observed value (vertical lines from the ends of the box) and outliers (circle).

Age effect

Table II shows the means and standard deviations of OT and the number of trials across all age groups. The number of trials to reach the stop criterion depended on the consistency of responses. Younger children needed more trials to finish the test than older ones (the 11-year-old children show an increase in the mean number of trials due to individual outliers). As illustrated in Fig. 1., the threshold values decreased with age. The Pearson correlations between age (in months) and OT (r = -0.387, P<0.01), as well as between age (in months) and number of trials (r = -0.25, P<0.05), showed significant, but only low age effects. It is striking that rather high inter-individual differences can be detected. For example, in the group of 9-year-old children, the range of values within one standard deviation lies between 39 ms and 109 ms. The age groups did not differ with respect to the number of boys and girls (Chi-Square test, $\chi^2 = 5.07$, df = 6, P<0.53). An analysis of variance showed no significant influence of gender on OT, even when age was taken as a covariate (F=1.26, df = 1, P<0.26).

Test-retest reliability after 1 week and after 4 months

Table III shows the means and standard deviations of the test and retest after 1 week and after 4 months. The arithmetic means of test and retest after a time interval of 1 week do not differ significantly (two-tailed test: t = 1.21, P<0.24). The moderate retest reliability is significant (Pearson's r = 0.53, P<0.02). To evaluate the stability over a longer time span, two measurements were

Table III

Stability and test-retest reliability over one week and over four months

Time interval	*n*	OT test (ms) mean ± SD	OT test (ms) mean ± SD	*t* (*P*)	*r* (*P*)
1 week	20	95 ± 41	85 ± 30	1.21 (0.24)	0.53 (0.02)
4 months	35	81 ± 38	66 ± 33	2.33 (0.03)	0.46 (0.01)

t-test values and the probability level (*P* (*t*-test)) for test-retest differences (*t*), and the correlation Pearson's coefficient (*r*) together with the probability level (*P*) for the test of significant correlations are indicated.

taken with a time interval of four months in between. The mean of the threshold values of the retest was significantly lower than the mean of the results of the first test. The differences between the results of the first test and the retest after four months were significant (two-tailed test: $t = 2.33$, $P<0.03$). The test-retest correlation was significant, but low (Pearson´s $r = 0.46$, $P<0.01$).

DISCUSSION

At which age is the OT task a useful diagnostic tool (feasibility)?

The purpose of this study was to investigate whether auditory temporal OT tasks can be reliably utilized to assess temporal-processing abilities in children. We found that a lot of pre-school children and young school children had difficulties following the instructions. In contrast, children between 9 and 11 years of age did not have any problems. The examiner must ensure that children who are seven years old or younger are able to perform the task. Only 60% of the pre-school children (5 and 6 years of age) were able to follow the instructions, as compared to 94% of the 7-year-old children. 100% of the children were able to follow the task only at an age of 9 and older. Our findings on feasibility are consistent with the results of other studies using auditory temporal-discrimination tasks. Thompson and co-workers (1999) also reported that most children in the 5-year-old group failed to meet the auditory-training criteria. On the other hand, infants – even in their first year – have the ability to discriminate temporal order (Benasich 1998). However, the results of OT judgment abilities in infants were collected using indirect assessment techniques, such as operantly-conditioned head turning. In contrast, the children in our study had to report their subjective impression explicitly. Our results show that the cognitive demands of this special test paradigm – the concept of comparative relation – are very high for younger children. Other specific procedures have to be developed to assess temporal thresholds of very young children. To sum up, OT judgment in children younger than 7 years can only be assessed with difficulty. Children at an age of 9 and above have no problems performing the task.

Are there age-related changes in auditory OT?

As reported in previous studies (Kegel et al. 1988, Szelag et al. 2004, Veit, unpublished results), we observed a decrease of the auditory OT with age. These studies indicate that the temporal OT reaches the adult level at approximately ten years of age. In our study, children at the age of 10 and 11 years had mean OTs of above 60 ms. OT values of adults usually lie in the range between 20 and 40 ms (Kanabus et al. 2002, Lotze et al. 1999). In contrast to gender, where no differences occurred, the specific age of a child has to be taken into account when interpreting its performance. Therefore, for the employment of a specific temporal-processing task in clinical practice, normative data for every age group have to be collected. It is noteworthy that there are no gender differences in children. In a study with the same OT-assessment technique, women needed longer inter-stimulus intervals than men before they were able to indicate the correct temporal order (Wittmann and Szelag 2003). Hence, gender differences in temporal-order judgments appear only after brain maturation has been completed.

What is the test-retest reliability of OT after a short period of one week (reliability) and over a longer time interval of four months (stability)?

We determined the test-retest reliability over one week. Only a moderate correlation emerged. To examine the stability of the auditory OT over a longer time span, we re-examined a group of children after an interval of four months. The mean OT decreased significantly from test to retest, which is in line with the age effect found in our study. The significant correlation between these two time points was only low. For the moderate-to-low correlations of test values over a period of one week and over a span of four months, factors such as motivation or attention probably come into play. Some children might have difficulties in adapting to the laboratory condition, where they have to repeatedly tell the temporal order of clicks by focusing attention on relevant cues of the acoustic signal. These circumstances might contribute to the variance in performance.

CONCLUSIONS

Our study indicates that reliability of OT assessment is moderate and stability is low in children and so far is not sufficient for use in individual cases. The OT tasks are difficult, even for many normally developing children below the age of seven. The test-retest reliability evaluation leads us to the conclusion that, as a diagnostic tool for assessing temporal-processing ability in children, the OT results have to be interpreted with caution. OT tasks have proven to be sensitive in groups of patients with aphasia or dyslexic children. The mean group thresholds of language-impaired subjects show an increase in comparison to a control group. Our findings with normally developing children show that the range of OTs is very large, meaning that high values can also be observed in individual, normally-developing children. Therefore, especially in children, a high threshold is not evidence of the etiopathogenesis of language or other cognitive disability. Before testing of OT can be included in clinical practice as a diagnostic tool, further studies must improve the reliability of assessment and supply reliable cut-off values for different age levels. Only then the assessment of OT and training procedures can become useful tools in the diagnosis and therapy of dyslexic or language-impaired children.

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