On the Development of Low-Level Auditory Discrimination and Deficits in Dyslexia

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Absolute auditory thresholds, frequency resolution and temporal resolution develop with age. It is still discussed whether low-level auditory performance is of clinical significance—specifically, for delayed maturation of central auditory processing. Recently, five new auditory tasks were used to study the development of low-level auditory discrimination. It was found that the development lasts up to the age of 16–18 years (on an average). Very similar tasks were now used with 432 controls and 250 dyslexic subjects in the age range of 7–22 years. For both groups the performance in one of the tasks was not related to the performance in another task indicating that the five tasks challenge independent subfunctions of auditory processing. Surprisingly high numbers of subjects were classified as low performers (LP), because they could not perform one or the other task at its easiest level and no threshold value could be assigned. For the dyslexics the incidence of LP was considerably increased in all tasks and age groups as compared with the age matched controls. The development of dynamic visual and optomotor functions and the corresponding deficits in dyslexia are discussed in relation to the auditory data presented here. Copyright © 2004 John Wiley & Sons, Ltd.

Keywords: auditory processing; development; dyslexia; intensity discrimination; frequency discrimination; temporal order judgement

INTRODUCTION

The acquisition of spoken language relies strongly on the functions of the auditory system. The acquisition of reading seems to rely mostly on visual and optomotor functions. Yet, when learning to read and write

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auditory functions may be of great help in the acquisition of spelling, which in turn will support the acquisition of reading. This might be true especially for the German language, in which the correct spelling of many words can be accessed by correct auditory discrimination. Also, delayed language development as a consequence of poor auditory functions may result in deficits of language processing used also when acquiring reading and spelling skills.

In fact, evidence was found that dyslexics have problems with low-level auditory and visual processing, namely deficits in auditory temporal and spectral resolution (Mc Anally & Stein, 1996; Wright, Lombardino, King, Leonard, & Merzenich, 1997; Tallal, 1980) and it was found that the sensitivity to dynamic auditory and visual non-linguistic stimuli can predict non-word reading ability in both dyslexic and normal readers (for review see Tallal, Merzenich, Miller, & Jenkins, 1998). Phonological awareness, thought to be crucial for learning to read and write (Landerl & Wimmer, 1994; Tallal, 1980), might depend on basic (low-level) auditory skills. By contrast, it was argued that impaired auditory low-level skills may neither be sufficient nor necessary prerequisites for developing dyslexia (Rosen, 1999; Watson & Muller, 1993) and that the auditory problems of dyslexics are specific to linguistic skills (Schulte–Körne, Deimel, Bartling, & Remschmidt, 1998).

Many behavioural studies suggest that various aspects of auditory perception of non-linguistic and language-related stimuli are largely mature by school age (Allen & Wightman, 1992; Allen, Wightman, Kistler, & Dolan, 1989; Nittrouer, 1996; Olsho, 1985; Schneider, Morongielleo, & Trehub, 1990; Trehub, Schneider, Morrongiello, & Thorpe, 1989; Walley & Carell, 1983; Walley, Pisoni, & Aslin, 1984; Wightman, Allen, Dolan, Kistler, & Jamieson, 1989). Other auditory abilities such as detecting frequency differences in long tones are thought to have reached adult levels already by the age of 6 months (Olsho, Koch, Carter, Halpin, & Spetner, 1988; Olsho, Schoon, Sakai, Turpin, & Sperduto, 1982). These perceptual abilities are thought to be modifiable in terms of an individual's auditory experience (Bradlow, Pisoni, Akahane-Yamada, & Tohkura, 1997; Elliott, Longinotti, Meyer, Raz, & Zucker, 1981; Trehub, Schneider, & Henderson, 1995) and may be at different developmental levels for different children at the same age.

When considering sensory functions in dyslexia one has to take into account the natural development during school age, i.e. beyond the age of 6 years. The differentiation of certain sounds contained in a language may continue to develop during school age, when language comprehension is not quite enough, because spelling relies at least in part on exact auditory analysis of spoken words.

The first aim of this study was to obtain information about the development of low-level auditory processing by probing selected basic auditory skills in various age groups using ad hoc paradigms, consisting of five subtests, such as frequency discrimination and gap detection, that do not require any language processing (Buunen & van Valkenburg, 1979). Each test required to hear the difference between two auditory signals in a two-alternative-forced choice task.

The tasks were selected on the basis of spectrograms of spoken words showing that fast changes in *intensity* and/or *frequency* are the rule, that there exist short temporal *gaps*, in which the acoustic signals are interrupted. Spoken words also contain short sounds of different frequencies that follow each other with very little time between them. The *time order* of such sequences should be preserved during the auditory processing. Finally, the temporal order of two equal signals arriving at the two ears at slightly different times should be perceived in order to be able to preserve the *side order*. Of course, one could select other acoustic aspects of speech, but we decided to use this limited number of most basic features to test the subjects.

As a second aim we intended to study whether dyslexic children exhibit developmental deficits in the performance of these auditory discrimination tasks. The idea is that low-level auditory deficits may be one source of spelling problems which in turn may create problems in acquiring reading skills. While speech comprehension in adult normal subjects does not depend critically on exact auditory processing, spelling may be more difficult to learn, when auditory support is poorly developed. Large groups of age-matched subjects were recruited to see the difference between the controls and the dyslexics.

The aim of the study was not to determine the threshold values for each subject as exactly as possible, but rather to collect a large database using standardized tests suitable for practical obligatory testing procedures.

The companion paper describes the effects of daily practice of these low-level auditory tasks and their transfer to the performance of language-related phonological tasks and to spelling (Schäffler, Sonntag, Hartnegg & Fischer, 2004).

METHODS

Control subjects were 401 native speakers of German aged between 7 and 17 years (219f, 182 m). They were recruited from primary and secondary schools in the Freiburg area. Another 31 control subjects aged between 18 and 22 years were students. None of the controls had any history of neurological, emotional or hearing problems (as tested by a pure tone audiogram) nor any signs of dyslexia as evidenced by their grades in school or by a German spelling test (DRT), which tests for single word spelling. The mean T-value for spelling was 50.1 ± 9.7 (N=210). General intelligence using non-verbal parts of the standardized HAWIK was tested in 31 of these control subjects with a mean IQ value of 111 ± 12. In a separate group of 81 control children the general intelligence was also measured by the HAWIK test.

Dyslexic subjects: A total of 250 dyslexic subjects (with an imbalance of 64f and 186 m) were recruited from German schools. In general, we used standardized German spelling (DRT, testing single word spelling) and reading tests (Züricher ZLT, testing for accuracy and reading rate) and compared the results with those of a standardized intelligence test (K-ABC or HAWIK). IQ values were available from 150 subjects with a mean value of 109 ± 12. The mean of the spelling percentile was below 25 or school grades for spelling and reading were below 4, while the other grades were greater than 3 at a scale of 1 (best) to 6 (worst).

The children passed the classical auditory test of absolute thresholds over a large frequency range (pure tone audiograms with deviations less than 20 dB(A)). No tests of phonological decoding were applied in this study. No further criteria assessed by visual or optomotor tasks were used. ADHD children, as diagnosed by professional resident psychiatrists, were excluded from this group.

In a separate group of 77 dyslexic children general intelligence was also measured by the HAWIK test.

Table 1. Mean age and S.D. in years and the number of subjects in each of the five age groups.

	Group 1	Group 2	Group 3	Group 4	Group 5
Controls	7.6 ± .5/121	9.5 ± .5/127	11.6 ± .6/120	15.1 ± 9/33	20.7 ± 1.0/31
Dyslexics	7.9 ± .3/46	9.4 ± .5/103	11.6 ± .8/80	14.9 ± .9/21	—

Table 1 summarizes the mean age, standard deviations and the numbers of subjects in each group.

Design: The discrimination thresholds for (1) intensity, (2) frequency and (3) temporal gap in a broadband noise were determined. In the fourth and fifth test the time-order judgement for monaural (4) and the side order for binaural (5) stimulation were determined. Verbal instructions were supported by visual illustrations of the tasks and key presses. Several practice trials preceded each individual test session. The order of the test sessions was always the same (in the order of above description).

All five discrimination tasks were based on a two-alternative-forced choice procedure. Two stimuli were presented one after the other. The subjects were required to press one of the two keys corresponding to their perception. Subjects were asked whether the second stimulus was louder (was higher, contained the gap, was higher, was presented to the right ear) than the first stimulus. Subjects were required to wait until the second stimulus was presented. No feedback was given during the test sessions.

The difficulty of the task was increased within each session by decreasing the difference between the two stimuli in steps of decreasing size (see below). For each task the threshold value was defined as the last correct response preceding the first of the three errors in a sequence of seven consecutive trials. This method was used to find the transition from series of ''almost all correct'' responses to series of ''50% correct'' responses. The algorithm does not imply that only seven trials were used to determine the threshold, because errors preceding this sequence may have occurred, but did not terminate the session. Each of the five sessions lasted about 4 min depending on the child's performance.

It was not the aim of this method to determine the threshold exactly, but rather to have a routine test for single subjects and compare the individual results with those of an age-matched group of controls having been tested by the same method.

Computer simulations of this algorithm showed that the turnover from 98% to 50% correct responses (the guess rate) is determined in 63.4% of the cases with a precision of ± 1 step. In 83.5% the error was ± 3 steps or less. On average the algorithm has a small tendency to judge the threshold ''lower''. This kind of precision can be considered as adequate given the much larger interindividual scatter in the data (see below). A more precise threshold determination would have required much longer testing times with the consequence of possible effects of fatigue and attention problems.

Stimuli: Intensity discrimination was measured with two white noise intervals 300 ms in duration. The interstimulus interval (ISI) was 150 ms. The reference signal was 55 dB(A), and each trial started with a test intensity of 63 dB(A). On each trial the difference between target and reference stimulus was decreased by 10% of its previous value.

Frequency discrimination was measured using a reference tone with 1000 Hz frequency, 300 ms in duration and 65 dB(A) intensity. The test tone started with 1100 Hz (same duration and intensity as the reference tone). ISI was 150 ms.

Gap detection was measured using 60 dB(A), 300 ms white noise tones, one of which contained the gap. The two tones were identical in duration regardless of the gap. Gap duration started with 40 ms. ISI was 300 ms.

For the monaural time-order judgement a 1000 Hz tone and a 1120 Hz tone were presented in random order. Subjects were asked to indicate whether the higher tone or the lower tone was presented second. Both tones were 200 ms long and had an intensity of 63 dB(A). The start value of the stimulus interval was 300 ms.

For the side-order threshold task clicks with 55 dB(A) were delivered one to the right and one to the left ear in the random order. Subjects were asked to indicate if they heard the second click from the left or the right. The start value of the stimulus interval was 300 ms.

The psychoacoustic procedures were carried out using a custom made hand held device with an built-in response key pad. A small LCD screen provided feedback only during the instruction trials. Stimuli were applied through headphones (Sony MDR-P70).

Data analysis: The subjects of both groups were classified into 4 age groups 7–8, 9–10, 11–13, 14–17 years. There was one more age group of controls: 18–22 years to show the adult level of performance for each task. Low-performance subjects were counted in each group (see the Result section). The distributions of the threshold values were determined for each age group. Especially for the young subjects these distributions were skewed. Therefore, the median values were used to show the average age development graphically.

Test–retest reliability was determined by using the two percentile values of 31 subjects, who performed the five tests twice. This way age effects were eliminated from these data. The five test–retest correlation coefficients were calculated as r=0.6 (p=0.005), r=0.8 ($p<0.0001$), r=0.4 (p= 0.02), r=0.9 ($p<0.0002$) and r=0.6 ($p<0.0001$). The scatter plots showed that the deviations of r from 1.0 were mostly caused by cases were the second value was 'better' than the first. This indicates (and will be shown in the companion paper) that the repeated performance of these auditory tasks is subjected to learning effects, which transfer to spelling. It will also become clear from the results that the reliability was good enough to differentiate between groups of dyslexics and controls.

RESULTS

Correlations with general intelligence: In a separate set of data from 158 subjects (81 control and 77 dyslexic children (age 7–15 years)), from which IQ values were available, we looked at possible correlations of the low-level auditory scores with intelligence scores using the HAWIK intelligence test. The mean age of the control children was 9.9 $\pm$ 1.8 years, the mean IQ was 109 $\pm$ 11. No significant correlations ($p<0.01$) were found between the IQ and any of the five task variables. The same result was obtained from the other group of 77 dyslexic children with a mean age of 9.4 ± 2.1 years and a mean IQ of 104 ± 13. Correlation coefficients were all below 0.2. In particular, this finding implies that there were children with low IQ values and high performance and children with high IQ values and low performance in one or more of the auditory tasks.

Correlations between spelling and auditory scores: For dyslexic subjects all spelling scores were below percentile 25 (most of them even zero) and for most of them the auditory scores were also below percentile 16 (most of these even zero, see below). Data of this kind produce floor effects and correlations can hardly be found. Therefore we used the spelling and auditory scores of 210 controls to see possible correlations. All five correlation coefficients, however, were below 0.2 and none of them reached a significance better than 1%.

Low performance: In both groups there were subjects who were unable to perceive any difference between the two stimuli in one or the other of the five tasks: they performed at chance level at the start value or reached only one step beyond (see Methods). In other words, they were guessing all from the beginning and no threshold value could be assigned even though the tasks were very easy. These subjects were classified as low performers (LP) with respect to the task under consideration.

Figure 1 shows the percent numbers of LP subjects for both groups and all tasks as a function of age. Note that all percent scales are the same to show directly the difference between the tasks. The data points at the right in each

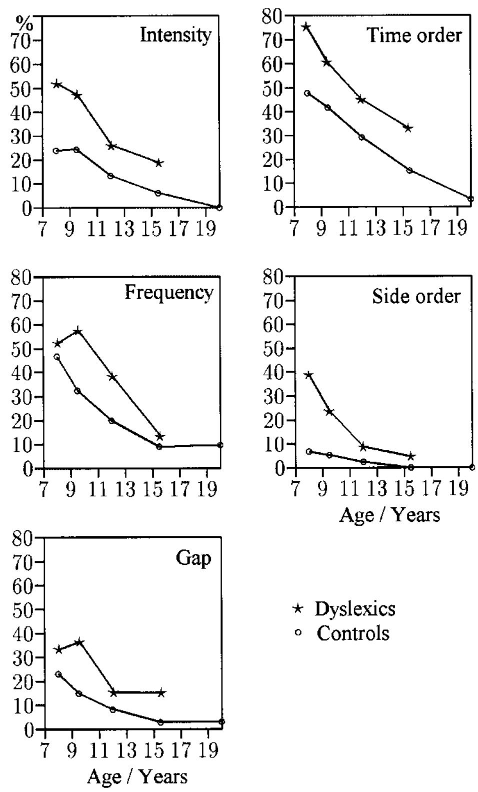

Figure 1. The percent numbers of subjects who performed at chance level (LP) for each task and group. The values on the right are obtained from the adult control subjects.

graph indicate the adult values, which are very close or equal to zero, with the exception of the frequency task, where the value is 10%.

The fact that so many of the young children could not do one or the other of the tasks better than by chance comes as a surprise, because the tasks with the start condition were really easy for a normal adult subject. Therefore, to further exclude the possibility that part of the children did not understand the tasks or the way of the required response, we counted for each subject the number of tasks that were not solved above chance level (*NL*).

Figure 2 shows the average of *NL* as a function of age for both groups. Even the youngest group of dyslexics performed above chance level in more than two of the tasks ($NL<3$). In fact, none of the controls and only 6% of the dyslexics failed in all five tasks. This indicates that the overwhelming majority (97.8%) of all subjects (N=651) of the present study understood the method of response, were motivated and also had the attention required to pass one or more of these auditory psychophysical tasks.

The curves of Figure 2 further indicate that with increasing age increasingly more of the tasks could be passed. The difference between the controls and the dyslexics was 0.8 averaged across age groups. An univariate ANOVA with age as covariate indicates highly significant effects for age (F=100.4, $p<0.0001$) and group (F=64.1, $p<0.0001$) and no interaction age $\times$ group.

To further quantify this observation we calculated the mean values of NL for each control group and counted the percent number of subjects, who exceeded this mean value by more than 1 S.D. in each age group (*limit*=*mean*+1 S.D.). The following limits were found for the different age groups: 3 for age group 1 and age group 2, 2 for age group 3 and 1 for age group 4. (Of course, the closest integer numbers were used for the limits). Table 2 gives the percent number of subjects falling outside these limits. By definition, there are also subjects among the controls, who fall beyond this criterion number. The last row of Table 2 presents the ratios of the two percent numbers. With the exception of the oldest group (containing only relatively few subjects) this factor is very close to 2. In

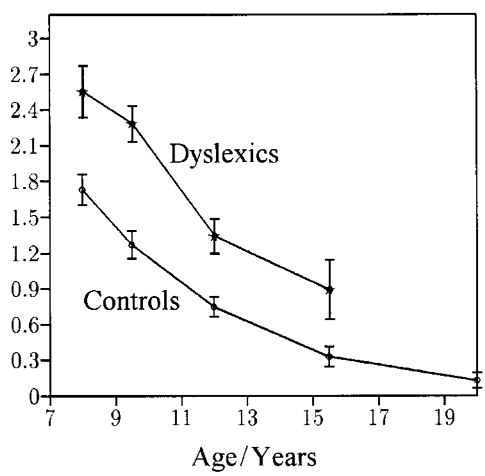

Figure 2. Mean number NL of tasks for each subject, that could not be performed above chance level. The right-most values are obtained from the adult control subjects. Vertical bars indicate the confidence intervals.

Table 2. Percent numbers of LP subjects in more than 3 or 2 or 1 of the tasks as indicated by the limit values in the upper row. These cutoff values were chosen according to the mean + 1 S.D. values of the controls (Figure 2)

	Group 1 (limit=3)	Group 2 (limit=3)	Group 3 (limit=2)	Group 4 (limit=1)
Controls (%)	28	19	21	33
Dyslexics (%)	56	39	43	45
Ratio	2.00	2.05	2.05	1.36

other words, the chances of a dyslexic subject to fail in more than the criterion number of tasks exceeds that of the controls by a factor of roughly 2.

Independence of task performance: The question of independence of the five tasks will be answered in two steps: (i) we consider the LP subjects, (ii) we consider the threshold values of the remaining tasks.

(i) For each age group and task we compared the probability for all subjects to achieve a low performance result in one test with the relative probability for each subgroup of subjects who also have low performance in one of the other tests. For example the fourth test (time-order judgement) was performed by 77 subjects of the third age group. Their results were classified as low performance in 25 cases. This is compared with the fraction of subjects with low performance in another test, e.g. 30 of this age group had low performance results in the frequency discrimination task. Fourteen of these 30 subjects (46.7%) showed low performance in both tests. This fraction is greater than 25 of 77 (32.5%).

The difference between these two values was calculated for all 20 possible pairs of tasks (4×5 tasks) for the first three age groups (the incidence of low performance in age group 4 was too low for this analysis) both for the group of dyslexics and controls. This yielded 60 possible values for the dyslexic group and 52 for the control group (because among the controls there were virtually no LP subjects for side-order judgement in age group 3 and therefore the $2 \times 4=8$ values of combinations with this test are missing).

To estimate the differences we measure them in units of their estimated limit of sampling error. Eleven of the 112 values differed by more than twice the error of measure. Four of them belonged to the control group and three of these indicated a dependence between frequency discrimination and time-order judgement. Among the dyslexics six differences involved side-order judgement and one involved gap detection.

In summary, the prediction of low performance in one task from low performance in another task is almost impossible in about 90% of the combinations. In the other cases there was no systematic pattern of certain tasks depending on certain other tasks.

While these considerations are of theoretical interest, they can also be extended with respect to practical implications for the application of the five auditory tasks. One can try to predict 'LP' for one task from the LP result of another task and calculate from the data as to how many false classifications would occur. The percentages of false classifications reach mean values between 62 and 69% for the controls and between 45 and 60% for the dyslexic group depending on age. (The lower error rates are obtained for the younger subjects, simply because there are

Table 3. The numbers in the table present the correlation coefficients and the *p*-values (below italic). Out of the 80 pairs of numbers only coefficients greater than 0.4 are depicted. Significant correlations at the 1% level are printed in bold. No correlations are detected in age group 3. Side-order performance did not correlate with any of the other task performances. For details see text

	Frequency		Gap		Time order	
	CON	DYS	CON	DYS	CON	DYS
Volume						
Age 1	**0.55**					
	0.00					
Age 2		**0.57**				
		0.002				
Age 4		**0.59**			**0.53**	0.52
		0.012			***0.003***	*0.083*
Frequency						
Age 1				0.54	**0.54**	0.42
				0.03	***0.003***	*0.255*
Age 2						**0.65**
						0.002
Age 4					**0.64**	**0.92**
					0.001	***0.000***
Gap						
Age 1						0.52
						0.186

more LP subjects among the younger as compared with the older groups.) The high error rates indicate that in practice each subject has to perform all five tasks to actually have an indication for LP performance.

(ii) For the subjects who were assigned a threshold value we calculated cross-correlations between the 10 possible pairs of the five test results for control and dyslexic group members in each of the four age bands. The results are listed in Table 3. Out of the 80 pairs of numbers only those 12 correlation coefficients are depicted that were greater than 0.4. Only seven of these correlations were significant at the 1% level (printed in bold).

No correlations coefficients above 0.4 were detected in age group 3. Side-order performance did not correlate with any of the other task performances better than 0.4.

Frequency discrimination or time-order judgement were included in all correlations above 0.4 and especially the correlations between these two tasks contribute five values out of the 12 listed in Table 3. Note also that eight of the correlations were found in the dyslexic groups. Both correlations including the gap detection task were not significant.

Therefore, the frequency discrimination and time-order tasks may be related to each other. This might be due to the fact that in both tasks a certain amount of frequency discrimination was necessary. Yet, there were many subjects who performed very poorly in one of these two tasks, (or were even LP subjects), but performed almost perfectly well in the other (see also Discussion). In the companion paper it is shown that frequency discrimination is easily improved by daily training, while time-order judgement is difficult.

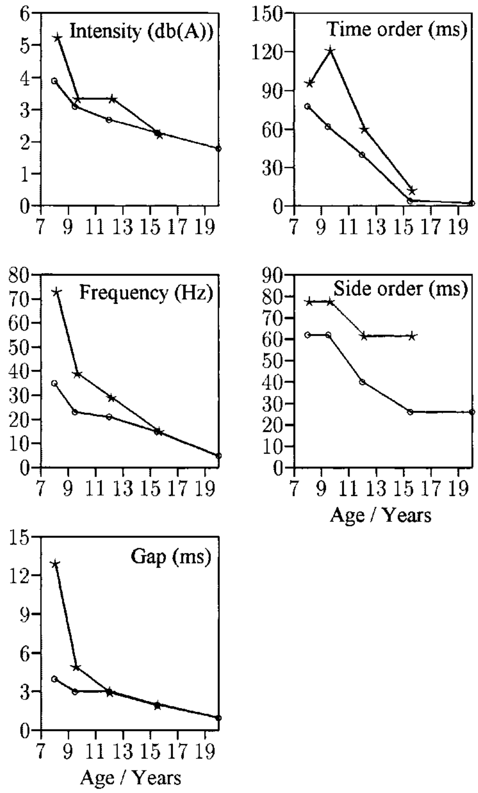

Figure 3. The median values are shown as a function of age for both groups of subjects and all 5 tasks. The values on the right are the medians obtained from the adult control subjects. No error bars are shown because the number of subjects performing beyond the 16-percentile are determined separately (see Table 5).

In conclusion, the result from a single subject in a given task could not reliably predict the result of the performance of another task.

These results suggest that the tasks probe specific and independent auditory subfunctions and not more general functional aspects like attentional resources and/or intellectual capacities.

Age dependence and group differences: For the subjects who passed the tasks above chance level, the median threshold values were calculated as a measure of the average performance of each age group (see Methods). Figure 3 shows the age curves for both groups of subjects and for all five tasks. All threshold values decreased with age.

An ANOVA was performed for each of the five variables with age as covariate. The results are summarized in Table 4. The performance of all five tasks depends significantly on age. Group effects, however, reached significance levels of 1% only for intensity discrimination and side-order judgement. Gap detection failed significance level of 5%. The other two tasks reached significance levels below 5%. There was no significant interaction of group x age, which reached a significance level of 1%.

We extended the analysis by counting the percent numbers of dyslexic subjects, who passed the tasks but performed below the 16th-percentile of the respective

Table 4. Result of ANOVA for all five task variables with age as covariate. Significant numbers are printed in bold. *F*-values are given with the *p*-values in brackets

	Group	Age	Group × age
Intensity	**12.0 (0.001)**	**53.9 (0.000)**	4.6 (0.032)
Frequency	5.7 (0.017)	**68.7 (0.000)**	1.4 (0.237)
Gap	2.8 (0.095)	**26.9 (0.000)**	0.2 (0.634)
Time order	6.5 (0.011)	**55.7 (0.000)**	1.8 (0.179)
Side order	**8.3 (0.004)**	**76.8 (0.000)**	3.4 (0.064)

Table 5. Percent numbers of dyslexic subjects, who performed beyond the 16th-percentile of the controls. Values above 25 are printed in bold

	Group 1	Group 2	Group 3	Group 4
Intensity	20	17	16	19
Frequency	**30**	8	16	19
Gap	**40**	25	19	25
Time order	9	21	18	10
Side order	**30**	**35**	20	21

controls. (By convention we used the 16th-percentile as a cutoff, because this number corresponds to 1 S.D. in a Gaussian distribution.) Table 5 shows that numbers exceeding 25 are found only in some age groups 1 and 2.

This result supports the ANOVA result that the main differences between the groups are found by the LP analysis (Figures 1 and 2 and Table 2), while the differentiation between the control group and the dyslexics becomes more difficult, when the LP subjects are already eliminated from the groups.

DISCUSSION

Similar to other studies our data indicate that low-level auditory skills as assessed by adhoc tasks presented here improve with increasing age (Allen *et al.*, 1989; Elliott & Hammer, 1988; Grose, Hall, & Gibbs, 1993; Hall & Grose, 1990, 1994; Maxon & Hochberg, 1982; Wightman *et al.*, 1989). The present data show in addition, however, that this development (on average) may last throughout school age. In particular, at the beginning of school age low-level auditory skills seem to be still poorly developed in most children as compared with the adults. The fact that certain proportions of children were classified as low performers can hardly be explained by the tasks being too difficult in their initial forms, because we have used considerably easier start values and still found LP subjects.

Considering these developmental aspects, it is of interest to note that dynamic vision and saccade control show similar time courses over the period of 7 to 17 years of age Biscaldi, Fischer, & Hartnegg, 2000; Fischer, Hartnegg, & Mokler, 2000; Schrauf, Wist, & Ehrenstein, 2000).

The percentages of dyslexics failing one or more of the auditory tasks may depend critically on a referral bias of the selection of subjects. In case the bias in our selection was toward dyslexic children with visual or optomotor problems the percentages given above are underestimated. In other words, the number of dyslexics with low-level auditory deficits would be even higher than reported here in a sample of 250 dyslexics. Meanwhile a still larger sample of 1284 dyslexics being tested by a very similar auditory test battery is available, in which a bias towards subjects with visual problems is very unlikely. The percentage of dyslexics with auditory deficits in the 5 domains are very similar to what is reported here (unpublished data).

Variables from individual auditory tasks of this study did not correlate (with the exception of the frequency discrimination task and the time-order task, see below). Similar results were obtained in earlier studies of adult subjects (Johnson, Watson, & Jensen, 1987) supporting the hypothesis that there exist specific subfunctions that together constitute the basis of the process of auditory perception very similar to the visual system where one also finds subsystems for different functions like orientation discrimination or processing of movement or perception of depth or colour.

The independence of the auditory subfunctions is also supported by the fact that by training a single subject with deficits in these domains may improve the deficits in one but not in the other domain (see companion paper). This is particularly important for frequency discrimination and time-order judgement which showed a correlation. But while frequency discrimination was easily learned by about 70% of the subjects, time order was learned by 36% only. The companion paper gives detailed information showing that it is hardly possible to predict the training results for one of the two tasks from those of the other task.

Since even within the same sensory system one or the other subfunction may be impaired while others are normal, one wants to be rather careful when generalizing from the results of small groups of subjects of a certain age having been tested by small batteries of tasks. For example, while frequency discrimination clearly differentiates dyslexics from controls in age group 2, no significant differences are found for older subjects in age group 4 (Figures 1 and 3, second panel). The specification of tasks and age is crucial for the question of whether a single child or a certain group of subjects differs from normal sensory performance. If, for example, no differences between groups were found using a specific task, this does not imply that there are no such differences, because the task may have been too easy (ceiling effect) or too difficult (floor effect). The tasks used in the present study yielded differences and therefore were easy and difficult enough to allow a differentiation. One of the reasons for the controversially discussed results on auditory deficits in dyslexia may be clarified when considering all these details.

The present study supports earlier notions that especially temporal auditory processing is impaired in many dyslexics (Tallal, 1980; Tallal & Katz, 1989; Witton *et al.*, 1998). Since other systems, the dynamic visual (Talcott, Hansen, Assoku, & Stein, 2002) and the optomotor systems may also exhibit deficits in dyslexic subjects (Conners, 1990; Fischer *et al.*, 2000; Biscaldi *et al.*, 2000; Stein & Talcott, 1999) it may be important to look at these deficits also when searching for specific sensory problems in the acquisition of reading and spelling skills, as has been suggested earlier (Fischer *et al.*, 2000).

Mechanisms of learning as discussed earlier (Merzenich & Sameshina, 1993) may be different for different auditory domains. From a subsequent study we know that daily practice easily improves some of the auditory skills tested in this study while others are difficult to learn. It has also been shown that the auditory training effects transfer to language-related phonological discrimination and to spelling (see companion paper).

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