Research Article

Auditory Processing Disorders with and without Central Auditory Discrimination Deficits

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Received: 25 June 2012; Accepted: 17 February 2014; Online publication: 22 March 2014

ABSTRACT

Auditory processing disorder (APD) is defined as a processing deficit in the auditory modality and spans multiple processes. To date, APD diagnosis is mostly based on the utilization of speech material. Adequate nonspeech tests that allow differentiation between an actual central hearing disorder and related disorders such as specific language impairments are still not adequately available. In the present study, 84 children between 6 and 17 years of age (clinical group), referred to three audiological centers for APD diagnosis, were evaluated with standard audiological tests and additional auditory discrimination tests. Latter tests assessed the processing of basic acoustic features at two different stages of the ascending central auditory system: (1) auditory brainstem processing was evaluated by quantifying interaural frequency, level, and signal duration discrimination (interaural tests). (2) Diencephalic/telencephalic processing was assessed by varying the same acoustic parameters

(plus signals with sinusoidal amplitude modulation), but presenting the test signals in conjunction with noise pulses to the contralateral ear (dichotic_{signal/noise} tests). Data of children in the clinical group were referenced to normative data obtained from more than 300 normally developing healthy school children. The results in the audiological and the discrimination tests diverged widely. Of the 39 children that were diagnosed with APD in the audiological clinic, 30 had deficits in auditory performance. Even more alarming was the fact that of the 45 children with a negative APD diagnosis, 32 showed clear signs of a central hearing deficit. Based on these results, we suggest revising current diagnostic procedure to evaluate APD in order to more clearly differentiate between central auditory processing deficits and higher-order (cognitive and/or language) processing deficits.

Keywords: APD, central auditory processing, discrimination performance, pure tone, children, clinical

The study was carried out in all institutions.

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INTRODUCTION

During the last 20 years, auditory processing disorder (APD) in children has gained recognition in clinical audiology. The term APD does not refer to a precisely

defined disorder, but rather to a collection of different functional impairments. Individuals with APD typically have difficulties in complex listening situations, such as understanding speech in background noise, rapid or degraded speech, and they have problems when comprehending verbal instructions (Jerger and Musiek 2000; Chermak 2002). The American Speech-Language-Hearing Association (ASHA) lists several auditory skills that can be impaired in APD, for example sound localization, auditory discrimination, temporal aspects of audition, and performance in competing acoustic signals (ASHA 1996; Chermak 2002; ASHA 2005).

Despite this comprehensive description, more recent research has questioned the original concept of APD as it was previously assumed. First, there is the question of how far attention and memory play a significant role in APD. There is no doubt that any test performed by a child uses cognitive resources. However, some researchers argue that APD is, at least partially, caused by higher-order impairments (Moore et al. 2010; BSA 2011), while others claim that APD and attentional problems are not always interrelated (Sharma et al. 2009). Second, there is an ongoing debate about the relation of APD and neurodevelopmental disorders such as specific language impairment (SLI) and dyslexia (King et al. 2003; Sharma et al. 2006, 2009; Dawes et al. 2008; Ferguson et al. 2011). These studies claim that there is hardly any difference in results of auditory processing (AP) measures between children with APD and children with language or reading impairments. Thus, the question arises whether APD is a discrete impairment that might co-occur with related neurodevelopmental disorders or whether these impairments rather, altogether, reflect a single, global disorder that manifests itself in multiple areas rather than individual, comorbid disorders (Sharma et al. 2009).

Almost all auditory skills described by the ASHA or the British Society of Audiology (BSA) can be investigated using both speech and nonspeech stimuli. Among others, there are tests investigating (1) localization or in the broadest sense spatial hearing using noise bursts (Kühnle et al. 2013) or speech (Cameron et al. 2006a, b), (2) discrimination of simple sounds (Dawes and Bishop 2008; Moore et al. 2011) or speech stimuli (Kraus et al. 1996), and even (3) binaural interaction based on clicks (Gopal and Pierel 1999; Delb et al. 2003) or speech sounds (Willeford 1985). If auditory processing is solely measured using speech sounds, then the criteria recently established by the BSA (2011) would not be met, namely that APD is characterized by poor perception of both speech and nonspeech sounds. Also, if an auditory deficit is manifested only in speech processing, it should not be recognized as APD (Dawes and Bishop 2009). Thus, it is indispensable to measure auditory processing based on nonverbal stimulus material. More

importantly, however, there are many children suspected of APD by their parents, teachers, or caregivers, but clinical (speech) tests still fail to reveal a deficit. The present paper focuses on the question of how far auditory processing deficits contribute to these children's everyday listening problems. Thereby, the focus is explicitly on *central* auditory processing.

Testing central auditory processing is challenging for a number of reasons: First, there is the above-mentioned link to the speech and language processing system. Furthermore, there is the particular anatomy and physiology of the auditory system. Unlike in other sensory systems, most fibers ascending from either auditory thalamus to the ipsilateral auditory cortex convey binaural input (guinea pig, Rutkowski et al. 2000; cat, Rosenzweig 1951; Morel and Imig 1987; and human, Celesia 1976) due to multiple ipsilateral and contralateral convergence in the auditory brainstem (Moore and Osen 1979; Nieuwenhuys 1984; Moore 1987; Bazwinsky et al. 2003). Still, there is evidence for a functional dominance of the connections from either ear to the contralateral auditory cortex (guinea pig, Popelar et al. 1994; nonhuman primates, Heffner and Heffner 1989; and human, Celesia 1976; Woldorff et al. 1999; Jäncke et al. 2002) leading to stronger and faster cortical activation mediated by the information from the contralateral ear (Hall and Goldstein 1968; Majkowski et al. 1971). Due to such multiple binaural convergences, hemisphere-specific testing of auditory structures is impossible using monaural tests, with signals being presented to one ear or even by the use of binaural tests, where identical stimuli are presented to both ears at the same time. In this context, it should be considered that a number of studies have shown that besides the hemispheric-specific processing of language, also other auditory functions/skills have a hemispheric-specific preponderance. Although definite allocation is still under debate, functional lateralization was, for example, reported for intensity discrimination (Belin et al. 1998; Brancucci et al. 2005), duration discrimination (Brechmann and Scheich 2005; Reiterer et al. 2005; Puschmann et al. 2012), and spectral and temporal processing (Schönwiesner et al. 2005; Zatorre and Belin 2011). So, any evaluation of APD should not ignore these possible lateralizations. In the present approach, we employed dichotic_{signal/noise} (dichotic_{s/n}) tests that generate different activation in both auditory cortices. In the cortex contralateral to the presented target signals, there is a stronger representation of the signals and a weaker representation of the noise, while in the ipsilateral cortex, the emphasis is reversed. Only recently, Brechmann and colleagues used this approach to reveal cortical lateralities that could not have been found without contralateral

white noise stimulation (Behne et al. 2005; Behne et al. 2006; Angenstein and Brechmann 2013). In the present tests, discrimination ability for the basic acoustic parameters frequency, level, duration, and amplitude modulation were measured using such dichotic_{s/n} presentation and by employing a 3IFC (3-interval forced choice) paradigm.

In other respects, there is evidence for a correlation of impaired auditory processing and subcortical auditory function as indicated by alterations in brainstem responses (King et al. 2002; Johnson et al. 2005; Banai et al. 2009). This correlation was found by employing speech stimuli. However, another important function of subcortical auditory areas is the preprocessing of spatial acoustic information (Tollin 2003; Kraus and Nicol 2005). This preprocessing comprises binaural integration of interaural frequency, time, and level differences in the auditory brainstem. Therefore, in the present study three tests employing nonspeech signals with interaural differences were used to investigate binaural integration ability of the auditory brainstem. Again, testing made use of the 3IFC paradigm to maintain test design and task demands. Evidence of the specificity of the discrimination tests comes, *inter alia*, from data in patients with acquired brain lesions in auditory areas of the brainstem or in the respective subcortical and cortical areas. The different lesions were specifically associated with impaired performance in either the dichotic_{s/n} tests or in the interaural tests (Bungert-Kahl et al. 2004; Biedermann et al. 2008). The same tests were used in the present study to better understand how central auditory processing deficits and the diagnosis APD relate to each other.

METHOD

Participants

Control group

A total of 313 children and adolescents (male, 156; female, 157) between 6 and 19 years of age (mean, 11.7; SD, 4.1) were examined with auditory discrimination tests. Participants were divided into seven age groups that included at least 10 boys and 10 girls for each single discrimination test (Table 1). Carrying out all tests one by one in a single participant would have required about 2 h. Due to the limited attention span in young children, only two to three tests were conducted with 6- and 7-year-old children in a single session. Thus, the age group 6/7 comprised more children than the other age groups. Test sessions (including required breaks) did not exceed 1 h for children up to the age of 13 years and 1.5 h for all other participants. Testing of control

TABLE 1

Participants taking part in the testing

Age group	Total n	Girls n	Boys n
6/7	68	33	35
8/9	46	23	23
10/11	40	20	20
12/13	42	17	25
14/15	39	20	19
16/17	33	17	16
18/19	35	17	18

participants was conducted in a quiet room of the Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig.

All children in the control group were school children recruited from schools (junior high and secondary schools) in the urban area of Leipzig, guaranteeing a representative mixture of cognitive capabilities and socioeconomic backgrounds in young participants. Children (or parents) were asked by questionnaire if they had or had been diagnosed with (1) general hearing problems, (2) frequent otitis media, (3) tinnitus, (4) injuries/operations on the head, (5) epilepsy, (6) APD, (7) problems with receptive/expressive speech or language, (8) dyslexia, and (9) therapeutic interventions from a speech-language pathologist prior to the investigation. Children that had one or more of these issues were not invited to participate. We obtained written consent from the parents of all children and teenagers that were tested. It should be noted that none of the children had a history of neurological disorders or suffered from head trauma or surgery, tinnitus, or attention deficit disorder/attention deficit hyperactivity disorder. They did not suffer from acute otologic diseases and had not been subjected to APD diagnostics before.

Clinical group

Participants were recruited from three audiological centers in Germany: (1) Section of Phoniatics and Audiology, University of Leipzig; (2) Section of Phoniatics and Pedaudiology, Georg-August University of Göttingen; and (3) Center of Audiology and Phoniatics, Chemnitz. Participants were tested in standard clinical shielded cabins in the three centers. Data from 84 children and adolescents (male, 61; female, 23) between 6 and 17 years of age (mean, 9.1; SD, 2.6) were included in this study. All children suspected of APD were referred to the centers by specialists for Otorhinolaryngology (ENT) or pediatricians. None of the clinical participants had known diagnoses of SLI or dyslexia. Due the amount of tests that had to be executed in the clinics (*cf.* sections “Audiological Test Repertoire” and “Psychoacoustic

Test Repertoire”), testing comprised—depending on the age of the children—between three and five test sessions taking place on different days. Test sessions (including required breaks) did not exceed 1 h.

The study was approved by the institutional review board of the Max Planck Institute for Human Cognitive and Brain Sciences as well as by the respective review boards of the three participating centers.

Testing the integrity of the peripheral auditory system

In addition to the above-mentioned questionnaire, children in the control group received a detailed audiogram (cf. ‘Psychoacoustic Procedure’—audiogram) to guarantee normal peripheral hearing.

Children in the clinical group received more extensive testing comprising the investigation of outer, middle, and inner ear function by ear microscopy, clinical audiograms, tympanograms, stapedius reflexes, and otoacoustic emissions. All participants exhibited audiometric air-conducted thresholds of 20 dB HL (ANSI 1996) or better for frequencies of 250–8,000 Hz at both ears as well as normal tympanograms, stapedius reflexes, and otoacoustic emissions. In case of impairments of the peripheral auditory system, they were not included in the study.

Audiological test repertoire

For audiological testing of central auditory function, the following skills were examined:

Speech intelligibility in quiet and in noise was determined using the “Freiburger Sprachaudiogramm” (speech audiogram; Keller 1977) or, in children aged 7 years or younger, the “Mainzer Sprachaudiogramm” (Biesalski et al. 1974). In the tests, participants are asked to correctly repeat 20 monosyllabic words at a presentation level of 65 dB sound pressure level (SPL). The test signals (recorded female voice) are presented through loudspeakers placed in front of the child (distance, 1 m). In the noise condition, a homogeneous noise field is generated by presenting the noise at a level of 60 dB SPL through a loudspeaker placed above the child. Speech intelligibility was considered normal with a score of at least 90 % correct in the quiet condition and no more than 15 % correct difference between the quiet and the noise conditions.

Dichotic speech discrimination was investigated using Feldmann’s dichotic speech test (Feldmann 1965). In this test, different trisyllabic words are presented to each ear via headphones (recorded male voice) (example, left—“Eisenbahn” [railway]; right—“Pinzelstrich” [stroke of the brush]) and the

children are asked to repeat both words correctly. The first 10 pairs were presented at a starting presentation level of 50 dB SPL. A score of 90 % correct for both ears was considered normal. In case of a lower score, presentation level was increased in 5-dB steps until the children reached 90 % correct. If a child scored below this criterion at all presentation levels, the test stopped at a maximum level of 80 dB SPL. In children up to the age of 8, an easier dichotic speech test (Uttenweiler 1980) was used, more suitable for younger children because of the choice of words (de Maddalena et al. 2001).

Auditory short-term memory was investigated using the Mottier (1951) test. In this test, meaningless words composed of two to six syllables (examples, ho-la; pe-ka-to-ri-se-ma), spoken by the examiner with lips shielded, had to be repeated correctly. Passing criteria were as follows: out of 30 items, 22 correct in 7-year olds, 23 in 8-year olds, 24 in 9- and 10-year olds, and 25 in 11- and 12-year olds.

Phonological differentiation was tested by the “Heidelberger Lautdifferenzierungstest” (Test for differentiation of spoken sounds). Two words (recorded female voice) were presented consecutively via loudspeakers at 65 dB SPL and had to be (1) categorized as “same” or “different” (subtest Ia; example, Kirche-Kirsche [church-cherry]) and (2) repeated correctly (subtest Ib). As a subtest for older children (second and fourth grade), the initial letters of both words had to be pronounced correctly (subtest II) (Brunner et al. 1998; Dierks et al. 1999).

Localization was tested in a setup with eight loudspeakers, separated by 45 ° in azimuth, thus spanning 360 °. Sinusoidally amplitude-modulated signals (SAM signals) (carrier frequency, 1 kHz; modulation frequency, 12 Hz; modulation depth, 7.5 %) had to be assigned to the correct loudspeaker. Presentation level was 30 dB SPL and could be increased up to 40 or 50 dB SPL if the child had problems assigning the respective loudspeaker correctly. Normal performance required the assignment of all signals to the correct loudspeakers in at least one stimulus condition (30, 40, or 50 dB SPL).

Additionally, brainstem-evoked response audiometry (BERA) and cerebral-evoked response audiometry (CERA) were used as objective measures. For the BERA, 80 dB SPL, 100 μ s click trains were presented at a rate of 18.5/s monaurally to either ear. Peak latencies of waves I, III, and V were analyzed and had to be in the normal range (I, 1.55 ms $\pm$ 40 ms; III, 3.7 ms $\pm$ 40 ms; and V, 5.6 ms $\pm$ 40 ms). Also, interpeak latencies between waves I and III and between waves III and V were evaluated (norms—I to III, 2.15 ms $\pm$ 30 ms; III to V, 1.85 ms $\pm$ 30 ms).

CERA was evoked by presenting 1-kHz tones, 200 ms in duration (including cosine-squared ramps of 10 ms) at a level of 80 dB SPL to either ear. Presentation rates were 0.2, 0.4, and 1.0 Hz, respectively. CERA was classified as abnormal when the peak latency of N1 (and the following P2) was larger than 200 ms or when the N1 was delayed by more than 100 ms between the 0.2-Hz condition and the 1.0-Hz condition.

Testing was conducted with standard audiometrical equipment (audiometer, Auritec® AT 900; headphones, Beyerdynamic® DT 48). Clinical evaluation of the children followed the guidelines of the German Society for Phoniatics and Pedaudiology: Children were diagnosed by audiologists as having APD (group “APD”) if three of the audiological tests yielded deficits in auditory performance despite age-matched hearing thresholds.

Psychoacoustic test repertoire

Apparatus and acoustic stimuli

Tone burst stimuli were generated using a real-time processor (RP2.1, Tucker-Davis-Technologies®, TDT, System III). Stimuli were amplified by a headphone buffer (HB7) and presented through circumaural headphones (Beyerdynamic®, DT 770 Pro). Stimulus synthesis and delivery as well as data recording made use of MATLAB 6.1 software (MathWorks Inc.®).

The audiogram was measured using pure tones at frequencies of 250, 500, 1,000, 2,000, 4,000, and 8,000 Hz. Stimuli for the discrimination tests were (a) pure tones at frequencies of 500 or 1,000 Hz; (b) SAM tone bursts with carrier frequencies of 500 or 1,000 Hz, a modulation frequency of 20 Hz, and 100 % modulation depth; and (c) broadband noise bursts (20 Hz to 10 kHz). The duration of all stimuli was 250 ms including cosine-squared ramps of 10 ms, interstimulus intervals were set to 750 ms. Signal level was adjusted to the individual hearing threshold (see below). Signal level was randomly varied by ± 3 dB in steps of 1 dB and frequency by ± 0.025 octaves in steps of 0.002 octaves from trial to trial.

Psychoacoustic procedure

Audiogram. Individual hearing thresholds for pure tones between 250 and 8,000 Hz and for the broadband noise signals were obtained at the beginning of each recording session using a yes/no (heard/not heard) paradigm. The respective threshold values were measured using an adaptive 1up–1down procedure (Levitt 1971). Starting levels were 60 dB SPL. Every change from a correct response (heard) to a negative response (not heard) and vice versa was marked as a reversal. The initial step size was 10 dB, which was

reduced to 2 dB after four reversals for a fine adjustment of the threshold. Each trial was terminated after eight reversals, and the arithmetic mean of the final four reversal points was taken as threshold. The respective threshold values for the 500 Hz, 1,000 Hz, and noise stimuli were used to set the presentation level for the subsequent discrimination tests at 35-dB sensation level (SL). This level guaranteed good audibility of the signals and prevented cross-talk from the stimulated ear through the head to the contralateral ear, which could have confounded the results.

Complete audiograms for all test frequencies were only obtained from control subjects to prove normal peripheral hearing. In the participants of the clinical group, normal middle and inner ear function had been verified by standard audiometric procedures (cf. “Audiological Test Repertoire”). For these participants, on the day of the tests, hearing thresholds were only measured for 500 Hz, 1,000 Hz, and for the noise band used to determine the presentation level for the discrimination tests.

Just noticeable differences. All discrimination tests were based on a 3IFC paradigm. Participants were asked to differentiate between two reference signals and one test signal differing in one single acoustic feature with the position of the test signal randomly altered within the stimulus triplet (Biedermann et al. 2008). Responses were given via pressing distinct buttons on a response box. Such tests are manageable even without the participants being aware of the specific acoustic property that was varied during testing. As long as the participants were able to apply the concept of “same” and “different” to three successively presented acoustic signals, and to indicate, with some consistency, the one detected as different, the tests yielded a reliable outcome. Such a standardized test design was chosen to minimize the amount of instructions necessary to explain every single test to the children.

The different presentation conditions have been described earlier in detail (Bungert-Kahl et al. 2004; Biedermann et al. 2008; Freigang et al. 2011). Briefly, discrimination thresholds were measured for the parameters frequency, level, signal duration, and for differences in amplitude modulation frequency. Two different test alternatives were used (Fig. 1) as follows:

First, in the interaural tests, stimuli were presented to both ears. Two binaurally identical signals were used as reference signals. The deviant signal had an interaural difference, i.e., the signal in one ear was (1) higher in frequency (frequency discrimination), (2) higher in level (level discrimination), or (3) shorter (duration discrimination). The

FIG. 1. 3IFC paradigm using the example of signal duration discrimination. Three consecutive signals were presented with the position of two reference signals and one deviant signal randomly varied. **A** Interaural presentation—reference signals (positions 1 and 3) are perceived as being one binaural single signal (virtually) located in the middle of the interaural axis; the deviant signal (position 2),

generates (in the case of duration discrimination) a signal being initially perceived in a central position and then moving to the side of the longer tone burst. **B** Dichotic_{signal/noise} presentation: One ear is stimulated with the respective reference (positions 1 and 2) and deviant signals (position 3); three identical noise bursts are simultaneously presented to the contralateral ear.

discrimination thresholds derived from stimuli of the type shown in Figure 1A will combine sensory coding in the brainstem for stimulus timing/pitch/level and binaural processing, and cortical processing needed to enable and indicate a correct judgment of the required response. All auditory tasks require some degree of cognitive (including language, memory, and decision processes) and motor (signaling the response) processing.

Second, in the dichotic_{signal/noise} condition (Fig. 1B), two reference signals and one deviant signal differing in the respective parameter being tested were presented to one ear. Additionally, three noise bursts were presented to the respective other ear. Stimuli of the type illustrated in Figure 1B will activate the auditory cortex of both hemispheres. The hemisphere contralateral to the tone stimuli is likely to play a larger part in contributing to the decision of “difference” than the ipsilateral hemisphere.

Frequency, level, and duration discrimination were performed in both conditions; SAM discrimination was only tested under dichotic_{s/n} condition.

Threshold estimation. Testing of acoustic feature discrimination in children critically depends on their comprehension of the tasks. Therefore, the tests started with three familiarization trials with large differences between deviant and reference signals. Feedback was provided for these familiarization trials. All participants who gave inconsistent responses or followed stereotyped response routines irrespective of the sequence of the stimuli (e.g., consistently always pressing the same button on the response box or consecutively pressing buttons 1, 2, and 3 over and over

again) were excluded from further tests. Those participants who responded consistently and hence proved to have good comprehension of the test design were included in the study.

For all discrimination tests, the procedure was as follows (see also Freigang et al. 2011). Invariably, the test procedure consisted of two phases: During the initial eight trials (first phase), the differences in the respective parameters were decreased stepwise starting from a large difference. See Table 2 for the initial differences and step sizes in the respective tests. Within these first eight trials, two incorrect responses in series stopped the first phase. If the participant performed the first eight trials correctly, the procedure carried on until the first incorrect response ended the first phase of the test. Participants’ responses obtained so far were used to estimate the psychometric function (Gelfand 1996) using a maximum likelihood procedure (Pentland 1980). As a basic form of the psychometric function, we applied a *logistic function* (1):

$$p(t) = x_4 + x_3 / (1 + \exp(-(t - x_1)x_2)) \quad (1)$$

where $p(t)$ is the probability of a correct response for a given Δ signal (i.e., Δ frequency, Δ level, Δ duration, and Δ modulation frequency). The functional form describes the transition from guess probability x_4 for small, nondetectable Δ signal ($1/3$ in a 3IFC experiment) to the higher plateau $p = x_4 + x_3$, reached at large t that becomes 1 for a perfectly performing participant. At $t = x_1$, $p(t)$ crosses the midpoint of the swing x_3 near $p = 2/3$. There, the slope of the function is proportional to x_2 . The variable t corresponds to the frequency difference in octaves, level difference in

TABLE 2

Threshold estimation—initial differences and step sizes

Test	Initial difference	Step size	Calculation
Dichotic _{s/n} duration	120 ms	10 ms	Additive
Interaural duration	120 ms	10 ms	Additive
Dichotic _{s/n} frequency	1.25 octave	0.4 × previous difference	Multiplicative
Interaural frequency	0.25 octave	0.5 × previous difference	Multiplicative
Dichotic _{s/n} level	20 dB	3 dB	Additive
Interaural level	20 dB	3 dB	Additive
Dichotic _{s/n} SAM	120 Hz	10 Hz	Additive

decibel, signal duration difference in milliseconds, and modulation frequency difference in Hertz, respectively.

In the 10 trials of the subsequent second phase, an adaptive procedure was employed to get a closer evaluation of the near-threshold range of discrimination. During this adaptive phase, the test variable for each following trial was taken from the actual estimate of the psychometric function as the specific value, which should lead to a hit response with a probability of approximately 0.4, 0.5, 0.8, or 0.9, the latter values taken in random order. At the end of this adaptive phase, the discrimination threshold was taken as the x_1 of the finally estimated logistic function. Such a single test typically lasted 2–3 min.

Statistical analysis

Normative data

In the assessment of clinical data, one must consider possible developmental changes in the ability to discriminate acoustic features in healthy, unimpaired children. Therefore, tests were also performed in normal-hearing children and adolescents between 6 and 19 years of age grouped in seven age groups. For every test, differences in median values and distribution between the age groups were investigated using the robust rank-order test (Siegel and Castellan 1988).

Rank tests are limited in that they do not measure the magnitude of the difference between test and control data if the test data falls outside the value range of the control. Such scaling would require knowledge of the “true” distribution of the control data. From the appropriate tests, we learned that it is not a Gaussian normal distribution. We therefore estimated the distribution by fitting a Weibull function to the threshold sample distribution:

$$W(t) = 1 - \exp\left(-\alpha(t-t_0)^\beta\right) \quad (\text{for } t \geq t_0, \text{ zero otherwise}) \quad (2)$$

In this three-parameter form, the Weibull function provides a good model for a wide range of distribu-

tion functions. Given a set of sample values, the optimum fitting parameters (t_0 , α , and β) can be found by applying the maximum likelihood principle. We performed this fitting for each test, test frequency and age group separately, applying methods of the MATLAB[®] Optimization Toolbox. As required, the Weibull approximation allows the scaling of the difference of patient thresholds even far outside the range of the control sample. However, working with normal distributions, especially with standard $N(0,1)$, is much more convenient and allows one to test with parametric tests. We therefore transformed the Weibull distributed thresholds t into $N(0,1)$ distributed z_c values using the function

$$g(t) = \Phi^{-1}(W(t)). \quad (3)$$

In (3), $\Phi^{-1}()$ is the inverse normal distribution function.

A possible age dependency of hearing thresholds was tested with Kruskal–Wallis one-way analysis of variance (ANOVA) on ranks with subsequent Mann–Whitney rank sum test.

Clinical group

The $N(0,1)$ property of the transformed control group distribution considerably simplifies comparing clinical thresholds to controls. For a single threshold (t_p), we only have to insert the threshold into the g function determined under the same condition (age cohort, test, and test frequency), getting $z_p = g(t_p)$. We then have to compare z_p with an appropriate significance limit of the $N(0,1)$ distribution for which we take 1.64, the upper 5 % error probability limit. If $z_p > 1.64$, we reject the null hypothesis that the threshold could stem from the control group and decide for an elevated subject threshold. The transformed thresholds [z_p] of the clinical group at the same age can be tested against the corresponding control values [z_c] by applying the two-sample t test.

Differences between the control group, the noAPD group, and the APD group were analyzed using

Kruskal–Wallis ANOVA on ranks with subsequent post hoc tests (Dunn’s method). The coherence between participants’ audiological and discrimination test results were assessed by chi-square test and (in case of less than five observations) Fisher’s exact test. Spearman rank correlation analyses were performed to investigate the relationship between discrimination tests that yielded abnormal results in the clinical groups. Only post hoc tests that were significant after Bonferroni correction at the 0.005 level are reported. A comparison of discrimination thresholds between the left and the right ear was done for all dichotic_{s/n} tests in the children showing a discrimination deficit using the Mann–Whitney rank sum test.

RESULTS

Normative data

Data from naïve, healthy children and adolescents between 6 and 19 years of age were collected to evaluate normal development of discrimination ability. These data are indispensable for a reliable assessment of discrimination performance in the clinical group reported below. Children from two successive years were pooled in one age cohort resulting in seven groups with at least 10 boys and 10 girls each (Table 3, Fig. 2).

The developmental course of the discrimination thresholds in the interaural and the dichotic_{s/n} tests (averaged for 500 and 1,000 Hz test frequencies) are shown in Figure 2 as improvement relative to the results of 6/7-year olds. The medians and interquartile ranges of the respective age groups are given in Table 3.

The discrimination tests in healthy, normally developing children show that much of the age-related changes in discrimination of basic acoustic parameters occur between 6/7 and 8/9 years of age. Six- and seven-year-old children have the highest thresholds and the largest intersubject variability. In the interaural tests, the discrimination thresholds for the three acoustic parameters frequency, level, and signal duration show differential developmental progressions. Frequency discrimination improves by 32 % up to the age of 10/11 (500 Hz, from 0.7 to 0.5 Hz; 1,000 Hz from 1.5 to 1.0 Hz) to reach adult-like values. In contrast, level processing shows a progressive improvement by up to 60 % up to the oldest age group (500 Hz, from 4.6 to 1.9 dB; 1,000 Hz, from 5.6 to 2.2 dB), also evidenced by the smallest median values and lowest intersubject variability. Still, threshold differences between groups of adolescents older than 12/13 years of age do not reach significance. Signal duration discrimination shows the strongest and fastest improvement amounting to 81 % (500 Hz,

from 33.1 to 6.8 ms; 1,000 Hz, 42.5 to 7.7 ms) in 10/11-year olds, after which values remain stable up to the age of 18/19. Except for the group of 6/7-year olds, interindividual variability is low for signal duration discrimination. Interestingly, some of the 6/7-year-old children are not able to master this test (see also Ludwig et al. 2012), and the data of these children were excluded from further analysis in the control group. As a consequence, in the subsequent analysis of the APD children, 6/7-year-old participants of the clinical group were not evaluated with this test.

The discrimination of the same parameters frequency, level, and signal duration plus modulation frequency (SAM) was also explored in the dichotic_{s/n} tests (Fig. 2). The same general improvement of discrimination ability with age can be observed, but for the different parameters the development is completed at different ages. Frequency, SAM, and signal duration discrimination mature first and are adult-like at the age of 10/11. Discrimination of level differences continues to improve up to 12/13 years of age. All these data were acquired as standard to identify a potentially aberrant development in children suspected of APD.

In addition to the discrimination ability, individual hearing thresholds for pure tones between 250 and 8,000 Hz were measured in healthy children of the respective age groups (Fig. 3). Hearing thresholds are about 30 dB SPL for 250 Hz and decrease with increasing frequency up to 4 kHz reaching median values between 3 and 6 dB SPL. From 4 to 8 kHz, thresholds increase by up to 20 dB. In contrast to discrimination thresholds, hearing sensitivity changes only slightly with increasing age. Age differences are found only at 1,000 Hz ($H_{(6)}=19.787$; $P=0.003$). In subsequent post hoc tests, significant differences are observed between age groups 16/17 and 8/9 ($T=368.5$; $P=0.003$) and between age groups 16/17 and 14/15 ($T=355.0$; $P=0.001$).

Clinical group

All 84 children included in the clinical group of this study had been referred to one of the three participating audiological centers by ENT specialists or pediatricians for the diagnosis of APD. Details of the results in the audiological tests can be found in the “Appendix” section.

Independent of the result of the diagnosis, all children were additionally subjected to the above described psychoacoustic discrimination tests investigating nonverbal central auditory processing. The tests were monitored by different investigators who had no knowledge of the audiological diagnosis. The results were correlated with the performance of age-

TABLE 3
Normative data—descriptive statistics

Interaural frequency							
Age group (N)	6/7 (21)	8/9 (22)	10/11 (22)	12/13 (21)	14/15 (20)	16/17 (20)	18/19 (20)
500 Hz							
25th Percentile (Hz)	0.6	0.4	0.3	0.3	0.3	0.3	0.3
Median (Hz)	0.7	0.6	0.5	0.4	0.5	0.5	0.4
75th Percentile (Hz)	1.1	0.8	0.6	0.5	0.7	0.7	0.7
1,000 Hz							
25th Percentile (Hz)	1.3	0.7	0.7	0.7	0.6	0.9	0.6
Median (Hz)	1.5	1.1	1.0	1.0	1.0	1.0	1.0
75th Percentile (Hz)	2.3	1.3	1.3	1.3	1.3	1.3	1.2
Interaural intensity							
Age group (N)	6/7 (19)	8/9 (20)	10/11 (21)	12/13 (20)	14/15 (22)	16/17 (22)	18/19 (22)
500 Hz							
25th Percentile (dB)	2.5	2.0	2.6	2.2	1.7	1.7	1.3
Median (dB)	4.6	2.9	3.3	3.1	2.8	2.9	1.9
75th Percentile (dB)	7.1	3.7	4.3	3.9	3.4	3.8	2.4
1,000 Hz							
25th Percentile (dB)	3.3	2.6	2.6	2.2	1.7	2.0	1.6
Median (dB)	5.6	4.0	3.6	3.8	2.9	2.9	2.2
75th Percentile (dB)	7.7	6.2	5.0	4.7	4.5	4.1	2.9
Interaural duration							
Age group (N)	6/7 ^a (13)	8/9 (23)	10/11 (22)	12/13 (23)	14/15 (21)	16/17 (23)	18/19 (22)
500 Hz							
25th Percentile (ms)	17.1	5.5	4.2	4.9	4.8	5.2	4.6
Median (ms)	33.1	8.4	6.8	7.7	7.3	6.8	6.2
75th Percentile (ms)	45.7	14.3	9.9	11.0	11.1	9.7	10.9
1,000 Hz							
25th Percentile (ms)	16.3	8.1	5.5	5.6	7.5	6.6	6.7
Median (ms)	42.5	14.4	7.7	8.9	10.0	9.2	11.1
75th Percentile (ms)	56.9	21.5	15.6	14.3	14.8	14.4	14.9
Dichotic _{s/n} frequency							
Age group (N)	6/7 (22)	8/9 (23)	10/11 (23)	12/13 (23)	14/15 (21)	16/17 (22)	18/19 (21)
500 Hz							
25th Percentile (Hz)	10.8	5.4	6.0	6.2	5.8	6.6	5.8
Median (Hz)	14.7	8.3	8.4	9.2	8.6	9.6	8.2
75th Percentile (Hz)	24.9	13.4	10.7	13.4	10.6	12.7	13.0
1,000 Hz							
25th Percentile (Hz)	14.8	10.8	8.9	10.3	9.9	9.8	7.6
Median (Hz)	22.8	15.0	13.2	13.4	12.4	13.0	12.0
75th Percentile (Hz)	42.8	19.5	18.3	19.9	15.6	17.0	15.5
Dichotic _{s/n} intensity							
Age group (N)	6/7 (22)	8/9 (22)	10/11 (21)	12/13 (22)	14/15 (21)	16/17 (21)	18/19 (20)
500 Hz							
25th Percentile (dB)	3.4	2.1	2.0	2.1	1.9	1.5	1.3
Median (dB)	4.9	3.7	2.8	2.9	2.6	2.0	2.2
75th Percentile (dB)	7.4	4.8	3.7	4.0	3.6	3.5	2.9
1,000 Hz							
25th Percentile (dB)	3.5	2.6	2.5	1.8	2.0	1.5	1.3
Median (dB)	5.6	4.2	3.4	2.9	3.0	2.7	2.5
75th Percentile (dB)	8.7	5.3	4.5	4.6	3.8	3.5	3.2
Dichotic _{s/n} duration							
Age group (N)	6/7 (21)	8/9 (22)	10/11 (25)	12/13 (24)	14/15 (22)	16/17 (20)	18/19 (21)
500 Hz							
25th Percentile (ms)	45.1	32.7	22.8	26.9	28.3	25.9	19.7
Median (ms)	57.5	43.6	31.5	33.5	33.0	31.6	27.2
75th Percentile (ms)	69.3	53.5	39.5	42.0	43.9	36.1	35.7
1000 Hz							
25th Percentile (ms)	40.4	33.9	27.1	29.3	32.0	25.5	22.9
Median (ms)	57.3	44.7	33.4	36.2	36.9	35.7	28.2
75th Percentile (ms)	74.6	60.1	43.2	47.4	44.1	40.4	35.8
Dichotic _{s/n} SAM							
Age group (N)	6/7 (27)	8/9 (22)	10/11 (21)	12/13 (22)	14/15 (21)	16/17 (20)	18/19 (22)

TABLE 3
(continued)

500 Hz							
25th Percentile (Hz)	10.2	6.2	5.3	4.9	6.9	5.2	4.9
Median (Hz)	21.6	9.2	8.3	8.0	10.4	8.4	7.8
75th Percentile (Hz)	39.7	15.9	12.7	12.3	12.4	11.5	13.2
1,000 Hz							
25th Percentile (Hz)	10.2	7.6	8.4	6.9	8.3	6.0	6.4
Median (Hz)	27.1	13.9	11.7	11.3	13.6	7.9	8.9
75th Percentile (Hz)	49.3	19.9	18.2	16.9	19.2	14.4	12.7

^aSome of the 6/7-year-old children were not able to accomplish the test of interaural duration discrimination. Values are given only for those children who successfully completed this test

Median, 25th, and 75th percentile in the respective age groups are listed for the parameters frequency (Hz), level (dB), signal duration (ms), and amplitude modulation (Hz) in both conditions (interaural and dichotic_{signal/noise}). Note that *N* per group is shown in brackets

matched normal-hearing children and the degree of deviation quantified by *z* equivalents (see “METHOD” section for the mode of calculation). Inherent in the calculation of *z* equivalents is the assumption that within a cohort of control subjects, 5 % of the individuals show elevated thresholds in a respective test. Therefore, a specific impairment in a clinical group is indicated by a significant increase in the incidence of threshold elevations.

Considering the results of the two independently acquired sets of tests (audiological, on the one hand, and nonverbal auditory discrimination, on the other hand), the children were classified into four groups: (1) APD and auditory discrimination deficits; (2) APD,

but no discrimination deficits; (3) noAPD and no discrimination deficits; and (4) noAPD, but discernible discrimination deficits. Table 4 gives an overview of the number and the percentage of children in the different groups.

In general, from the total of 84 children tested, 74 % (62 children) have discrimination deficits. The test results allowed differentiation between impairment of the auditory brainstem processing indicated by elevated thresholds in interaural frequency and duration discrimination and deficits of cortical/thalamic processing recognizable from alterations in dichotic_{s/n} frequency, amplitude modulation, and duration discrimination (see Biedermann et al. 2008 for details).

FIG. 2. Normative data. Improvement in discrimination performance referenced to the performance in 6/7-year-old children for interaural (left) and dichotic_{s/n} (right) discrimination tests (averaged data of 500 and 1,000 Hz test frequency) with parameters level (circles), frequency (squares), signal duration (diamonds), and sinusoidally amplitude modulated signals (SAM; triangles). Improvement was calculated as $\text{Imp} = 100 \times (\text{Thr}_1 - \text{Thr}_k) / \text{Thr}_1$, where Thr_1 is the median threshold of 6/7-year olds and Thr_k is the median of the respective other age groups. Improvement of interquartile ranges (interindividual variability) was quantified in the same way. Symbols show improvement of median values; dotted lines with crosses show the corresponding interquartile ranges (deviation). Open symbols

indicate the age group from which no further significant improvement in discrimination was found. Note that for different acoustic features, discrimination ability shows different developmental courses. While interaural frequency discrimination is fully mature at 10/11 years of age, interaural level discrimination capability steadily improves in part up to 19 years of age. Also for dichotic_{s/n} signal presentation, discrimination ability shows distinct developmental courses for the respective tests. There is a trend for a narrowing of the interquartile ranges indicating a reduction of interindividual variability with increasing age. Values for 500 and 1,000 Hz test frequency are averaged for visualization purposes.

FIG. 3. Audiograms. Hearing thresholds in decibel SPL plotted against test frequency for the different age groups. Box plots show median (black line), 25th and 75th percentile (boxes), and 10th and 90th percentile (whiskers). Note that a logarithmic (log) scale is used for the frequency axis.

Figure 4 shows for the interaural tests the results of the norm group and of the clinical group, which comprises APD children and noAPD children. In accordance with the basic assumption for the calculation of the z equivalents, in all tests, the respective values for the discrimination thresholds in the norm group do not exceed 1.64. Both the APD children and the noAPD children show significantly elevated thresholds. While there is a tendency for the children of the APD group to have the highest discrimination thresholds, the threshold differences between the APD group and the noAPD group are significant only for frequency discrimination at 1,000 Hz (Fig. 4, Table 5). When comparing the interquartile ranges, there are fewer children with discrimination deficits in the noAPD group compared to the APD group.

Also in the dichotic_{s/n} tests (Fig. 5), the APD group contains the largest number of children with discrimination deficits. Again, there are significant differences between APD children and children in the norm group in every discrimination test (Table 5), but significant differences between APD children and noAPD children can only be found for SAM discrimination (1,000 Hz). NoAPD children show significant differences compared to children in the norm group in every condition except

level discrimination (500 Hz) and SAM discrimination (1,000 Hz). In particular duration discrimination is impaired in APD and noAPD children with more than 50 % of children showing elevated discrimination thresholds in every group.

The data of children with discrimination deficits were additionally tested for differences in processing between both auditory cortices based on the results from the dichotic_{s/n} tests. There were no discernable differences between thresholds measured with signal presentation to the left or to the right ear. Thus, it appears unlikely that the observed processing deficit is assigned to either cortical hemisphere.

Taken together, both clinical subgroups significantly differ from children in the norm group but the diagnosis APD does not differentiate between children with and without central auditory discrimination deficits. In total, psychoacoustic and audiological evaluations match for noAPD-noDD in 13 % of cases and for APD-DD in 36 % of cases.

Figure 6 shows the absolute number of tests with elevated discrimination thresholds in APD and noAPD children; “0” indicates all test results were in the range of the age-matched control group and “7” threshold elevations were found in all tests. Children in the clinical group mostly had impaired discrimination, whether diagnosed with APD or not. However, those diagnosed tended to perform poorly on more tests than those not diagnosed. In the noAPD group, 13 children had no central auditory discrimination deficit at all. In these, the clinical diagnosis matched the psychoacoustic evaluation. Sixteen children had deficits in one test and 11 children in two tests. Five children were more severely impaired and had elevated thresholds in four or five tests. Altogether, 32 children who were not clinically diagnosed with APD showed clear signs of an auditory discrimination deficit.

TABLE 4

Contingency table of the number of children in the different groups

	APD	noAPD	sum
DD	30 (36 %)	32 (38 %)	62 (74 %)
noDD	9 (11 %)	13 (15 %)	22 (26 %)
sum	39	45	84

APD children diagnosed as having APD, noAPD children having no auditory processing disorder, DD children who had significantly elevated discrimination thresholds, noDD children who had no discrimination deficit

FIG. 4. Interaural tests. z Equivalents plotted for interaural frequency (upper left), level (upper right), and duration (lower left) discrimination. Box plots show median (black line), 25th and 75th percentile (boxes), and 10th and 90th percentile for 500 and 1,000 Hz test frequency, dashed lines designate significance level (1.64) in all panels. Box plots show data of healthy children (“Norm”; white, $n=132$), noAPD children (light gray, $n=32$), and APD children

(dark gray, $n=30$). Asterisks depict differences between groups at the 0.05 level. Note that both the APD children and the noAPD children show elevated discrimination thresholds compared to norm group. Table 5 specifies that this holds for all discrimination tests. Except for interaural frequency discrimination (1,000 Hz), there are no differences between APD and noAPD children.

Most of the children diagnosed with APD had elevated discrimination thresholds in one to three tests. Only in two children was the performance in all or almost all tests significantly impaired compared to age-matched controls. It cannot be ruled out that the latter children suffer from a more generalized (cognitive)

impairment that affects performance independent of the tested acoustic parameter or presentation design. However, all other children in the APD group performed in at least one or two tests within the normal range. This can be seen as an indication that the elevated thresholds are not the result of impaired

TABLE 5								
Differences between healthy children, noAPD children, and APD children								
Test	H (500 Hz)	H (1,000 Hz)	Norm vs. noAPD		Norm vs. APD		noAPD vs. APD	
			500 Hz	1,000 Hz	500 Hz	1,000 Hz	500 Hz	1,000 Hz
Interaural frequency	37.111	23.746	x		x	x		x
Interaural level	18.266	38.506	x	x	x	x		
Interaural duration	43.188	63.190	x	x	x	x		
Dichotic _{s/n} frequency	86.361	107.815	x	x	x	x		
Dichotic _{s/n} level	15.035	20.597		x	x	x		
Dichotic _{s/n} duration	124.150	115.198	x	x	x	x		
Dichotic _{s/n} SAM	42.974	42.309	x		x	x		x

Test statistics of Kruskal–Wallis ANOVA on ranks, all comparisons were significant ($P<0.001$) with 2 *df*. Post hoc tests (Dunn’s method) that revealed significant differences ($P<0.05$) are marked with x in columns 4 to 6

FIG. 5. Dichotic_{s/n} tests. z Equivalents plotted for dichotic_{s/n} frequency (upper left), level (upper right), duration (lower left), and SAM (lower right) discrimination. Design of the graph as in Figure 4. There are significant differences between APD children and healthy children in every discrimination test. The same holds true for noAPD

children with two exceptions (500 Hz level discrimination and 1,000 Hz SAM discrimination). Except for 1,000 Hz SAM discrimination, there are no significant differences between noAPD children and healthy children.

memory, task understanding, attention, or distractibility. Instead, the test results indicate specific central auditory discrimination deficits.

When comparing APD and noAPD children, it is also necessary to evaluate possible systematic interdependencies in performance in the different psychoacoustic discrimination tests. For that, we compared the interrelation between the threshold values in the different tests for each child (Fig. 7). After applying the Bonferroni correction for multiple comparisons, only a single significant positive correlation was evident, i.e., the one between the dichotic_{s/n} frequency and dichotic_{s/n} duration discrimination ($R^2_{(158)}=0.054$, $P=0.00307$; upper right panel in Fig. 7). Still, this linear model is not a reliable predictor of the data because it explains only 5.4 % of the variance. Also, noAPD and APD children showed no specific clustering of corresponding values. Therefore, the analysis does not support the notion of fundamental differences between APD and noAPD children with respect to central auditory discrimination performance.

Given the discrepancy between the audiological APD diagnosis and the results of auditory discrimination tests,

we explored the data for any potential correspondence between the outcome of audiological and psychoacoustic discrimination tests. For all individuals, the results were compared for each audiological and each discrimination test using chi-square test/Fisher's exact test (Table 6). The comparison yielded no significant relations between discrimination deficits in specific acoustic parameters and abnormal audiological test results.

DISCUSSION

The present study investigated the processing of basic acoustic features in children suspected of APD. Young participants were diagnosed as suffering from APD or not by audiologists on the basis of defined guidelines in three participating medical centers. In the same children, the discrimination thresholds for the basic acoustic features frequency, level, signal duration, and amplitude modulation were obtained through psychoacoustic tests and the performance compared with age-matched normative data. For each child, results in the discrimination tests were then contrasted with the

FIG. 6. Incidences of abnormal tests. Number of noAPD children (light gray bars) and APD children (dark gray bars) with 0–7 abnormal tests. Note that, in contrast to the clinical evaluation, nine APD children had no discrimination deficit at all (zero abnormal tests) and 32 of the noAPD children had abnormal values in one to five tests.

diagnosis obtained in clinical audiology to get a better understanding of how central auditory processing deficits and the diagnosis of APD relate to each other.

Normal development of central auditory processing

The results of the normative control group document the prolonged development of discrimination perfor-

mance for basic acoustic parameters with different acoustic cues showing differential developmental dynamics. The respective improvement is not only evidenced by better discrimination performance, but also by reduced interindividual variability. Interaural and dichotic_{s/n} frequency discrimination as well as interaural duration and dichotic_{s/n} amplitude modulation discrimination mature first and are adult-like by 11/12 years of age. In contrast, maturation of level discrimination (both conditions) and dichotic_{s/n} duration discrimination continues up to early teens. This is in accordance with studies showing different developmental courses in different tasks: temporal analysis matures later than the “spectral” analysis (Dawes and Bishop 2008; Banai et al. 2011) and auditory processing undergoes pronounced development until at least 11 years of age (Hartley et al. 1999, 2000).

Children suspected of auditory processing disorders

The present results emphasize that the children’s performance in the central auditory tests are not in accordance with the results of clinical APD diagnosis—in those 39 children that were diagnosed with APD in the audiological clinic, just 30 had deficits in central auditory processing. Even more relevant is

FIG. 7. Interrelation between dichotic s/n tests. z Equivalents for different discrimination tests plotted in relation to each other for noAPD children (dark blue 500 Hz, light blue 1,000 Hz) and APD children (dark red 500 Hz, light red 1,000 Hz). Dots enclosed by the gray dashed line depict nonsignificant values

TABLE 6

Interrelation between audiological tests and parameter discrimination					
Audiology	Phonological differentiation	Speech in noise	Dichotic speech test	Short-term memory	Localization
<i>Discrimination</i>					
Dichotic _{s/n} duration	0.62	0.89	0.21	0.46	0.43
Interaural duration	0.29	0.7	1.0	0.66	0.68
Dichotic _{s/n} frequency	0.19	0.44	0.093	1.0	0.7
Interaural frequency	0.055	1.0	0.59	0.66	0.66
Dichotic _{c/s/n} level	1.0	1.0	1.0	1.0	1.0
Interaural level	1.0	0.28	0.095	1.0	1.0
Dichotic _{s/n} SAM	0.22	1.0	0.11	1.0	1.0

Impaired performance in audiological tests was tested against elevated discrimination thresholds, chi-square test/Fisher's exact test, *P* values. Note that none of the *P* values reached significance level

the fact that 32 of the 45 children, in whom the diagnosis of APD was not clinically confirmed, still had significantly impaired auditory discrimination abilities. This is in accordance with other studies that failed to reveal correspondence between auditory deficits and APD diagnosis (Dawes et al. 2009; Ferguson et al. 2011). These discrepancies on the one hand give rise to questions related to the diagnosis of APD in daily clinical practice, but on the other hand might also concern the nature of APD as a clinical syndrome.

Children with auditory processing disorders

During the last decade, there has been much controversy about what defines APD. A close relationship was reported between APD and other developmental disorders such as SLI (Dawes and Bishop 2009; Sharma et al. 2009; Boscaroli et al. 2011; Ferguson et al. 2011) or dyslexia (King et al. 2003; Dawes and Bishop 2009; Dawes et al. 2009; Miller 2011). Some authors argue that there is hardly any difference between these impairments, and the fact that they may or may not co-occur (Dawes and Bishop 2009; Miller 2011) limits any attempt to disentangle whether and how these disorders are causally linked. Discussions even consider that all three disorders are different aspects of a generalized neurodevelopmental disorder. However, the present results in children with (suspected) APD, but without associated language and reading impairments, speak in favor of a disorder that can occur separately. This does not imply that APD may not occur with other developmental disorders. However, the present data do not support the hypothesis of a generalized neurodevelopmental disorder.

In Germany, APD diagnosis is primarily based on the evaluation of speech processing. In the present study, a number of children diagnosed with APD did not show impairments in discrimination of basic acoustic features, which—in accordance with the above statement—points to the fact that both impair-

ments are not necessarily interrelated. The results also reveal that the current clinical diagnostics do not allow the evaluation of *auditory* dysfunctions and their demarcation from receptive speech disorders. Still, a differentiation between auditory, i.e., sensory perceptual and cognitive or linguistic disorders is an important issue (Fitzgibbons and Gordon-Salant 1996; Cacace and McFarland 1998), also because APD is not always accompanied by weak phonological awareness (Sharma et al. 2006). All this points to the need to clearly differentiate APD from speech disorders, which necessitates the inclusion of nonlinguistic test material (Moore 2006; Moore et al. 2011). The BSA recently introduced a new consensus on a working definition: “APD is characterized by poor perception of both speech and non-speech sounds.” (BSA 2011). Explicitly referring to “nonspeech sounds” emphasizes the difference to linguistic processing (Hind 2006). The BSA further points out “... poor perception of speech alone is not sufficient evidence of APD.” Such reconsideration might be a step towards a better delineation and characterization of APD.

If one considers that the presently investigated children diagnosed with APD despite not having any auditory discrimination deficit had been evaluated predominantly on the basis of speech tests, one could hypothesize that these children show signs of a speech or language disorder rather than of an auditory processing deficit. Furthermore, these children do not always show deficits in the same clinical tests. In some children, phonological differentiation and dichotic listening was impaired, while others showed abnormal results in auditory short-term memory and in speech in noise. So, based on the present results and considering other recently published data (Wilson and Arnott 2013, see also below), it seems advisable to specify the diagnosis APD. One option would be to differentiate on the one hand APD with or without underlying auditory processing deficits and on the other hand APD with an emphasis on the

specific impairment (e.g., speech in noise or auditory short-term memory).

Children with discrimination deficits

Indeed, a number of children diagnosed as having APD also showed impairments of auditory discrimination. However, there are a significant number of children (about 74 % of all referrals) that clearly suffered from auditory processing deficits, yet in 32 children (38 %) clinical diagnostics failed to reveal APD. The question may arise, why it is important to search for impairments of central auditory abilities in these children, since—as mentioned before—doubts have been raised about the relationship between auditory discrimination ability and, for example, speech processing and cognitive skills in healthy subjects (Watson and Kidd 2002; Watson et al. 2003). Also, speech processing seems to be a robust process that requires only a minimal amount of spectral information, if temporal cues are available (Shannon et al. 1995). However, there are also contrary results in healthy children suggesting, for example, a correlation of the ability to detect frequency modulation and phonological skills (Witton et al. 1998; Talcott et al. 2000, 2002). Second, a possible lack of the respective correspondence in healthy children cannot necessarily be extrapolated to children with processing deficits: There is some evidence that abnormal frequency modulation detection correlates with impaired reading abilities (Witton et al. 1998), and poor frequency resolution correlates with poor communications skills (Moore 2012). Third, clinical assessment should delineate the cause of a listening problem and distinguish auditory problems from other deficits that may be similarly present (Rosen et al. 2010).

The reported lack of correspondence between auditory skills and speech processing might be in part due to specificities of the respective signal presentation. Some of the presently observed discrimination deficits could be revealed by the use of dichotic_{signal/noise} presentation. Already, Blaettner et al. (1989) used nonspeech discrimination tests with dichotic_{signal/noise} presentation and reported contralateral (or in their case contralesional) discrimination deficits. Furthermore, these authors also found evidence that the self-reported hearing problems of the patients, which had not been detected with monaural speech tests, corresponded well with their abnormal performance in the dichotic nonspeech tests. Also, the respective hearing problems mainly occurred in difficult hearing environments, a symptom that closely corresponds to the difficulties that our young patients experience. In the present study, the noAPD children who showed discrimination deficits had been referred to the pediatric audiological clinics because of listening problems at home or in school, and it became apparent that they indeed had impaired

auditory processing (manifested as a discrimination deficit) which audiological tests could not detect. Although these children do not have a diagnosed APD, as currently defined by the German Audiological Society, their central auditory processing deficiencies are likely to have an impact on important communication skills including, for example, speech understanding under challenging listening conditions.

Discrimination deficits and possible top-down engagement

It has been hypothesized that deficits seen in children with impaired auditory processing might not only arise from deficits in the ascending auditory pathway (bottom-up) but also from impaired top-down processes possibly also affecting the efferent central auditory system, i.e., structures that mediate auditory processing by attention and memory (Moore et al. 2010; Moore 2012). Other studies reported that correlations between auditory tasks and cognitive measures are weak or non-existent (Rosen et al. 2010), and that, in those children, attention and memory only explain a small amount of variance (Sharma et al. 2009). For the presently observed deficits in frequency and temporal processing under interaural and dichotic_{s/n} conditions, a distinction between bottom-up or top-down influences cannot easily be made, since all tests cause the same attentional load, and the same memory load, i.e., they use the same 3IFC paradigm and they all start with equally easy to discriminate signal differences. Still, the fact that in most cases frequency and duration discrimination, but not level discrimination, were impaired might speak for a deficit that is not the result of a supramodal cause. As several authors have pointed out, it is helpful to employ different auditory tasks that match in cognitive demands when dealing with such an issue (Katz and Tillery 2005; Rosen 2005). If a participant then fails in one test version (here, frequency discrimination), and not in another (here, level discrimination), it speaks in favor of the specificity of the deficit in the auditory domain rather than in favor of a supramodal cause of the impairment.

Still, some of the discrimination tests reveal developmental asynchrony. Some of the normally developing 6/7-year-old children were unable to master the test of interaural duration discrimination, while performing well in the others. We analyzed these children separately utilizing EEG (electroencephalogram) (Ludwig et al. 2012) and found that the children's central auditory system is capable of automatic change detection of interaural duration differences at this age, but active discrimination is far behind the performance of older participants. Therefore, in the present study, we refrain from testing 6/7-year-old children suspected of APD

with interaural duration discrimination. These results, again, point to the necessity of reliable normative data as acquired in the present study.

The apparent discrimination deficits in the dichotic_{s/n} condition could, at least partly, be explained by the influence of the *subcortical* efferent central auditory system, more specifically the medial olivocochlear bundle (MOCB; see Guinan 2006 for an overview). The function of the MOCB can be investigated by measuring otoacoustic emissions (OAE). The amplitude of OAE can be reduced by contralateral acoustic stimulation (Warren and Liberman 1989; Collet et al. 1990; Ryan et al. 1991; Berlin et al. 1993b), which is described as OAE suppression effect. This OAE suppression is related to speech understanding in noise (Kumar and Vanaja 2004) and is diminished (or even absent) in patients with speech in noise understanding impairments (Berlin et al. 1993a; Starr et al. 1996). The frequently observed deterioration of symptoms in APD children in noisy surroundings (ASHA 1996, 2005) could point towards a reduced function of the MOCB in this patient group. Actually, not only reduced OAE suppression effects but also generally larger amplitudes of OAE were found in APD children suggesting an impaired function of the efferent central auditory system (Muchnik et al. 2004; Moore 2006). The presently measured elevated thresholds in the dichotic_{s/n} condition could—at least in part—result from impaired function of the MOCB. The noise presented to one ear enhances stability and frequency selectivity of the contralateral basilar membrane via efferent pathways of the MOCB. A loss of this enhancement could have led to the elevated thresholds in dichotic_{s/n} frequency and duration discrimination.

Auditory impairments

More than 50 % of the children referred to the pediatric audiological centers showed impairments in central auditory processing. In the majority of cases, deficits were apparent in discrimination of dichotically_{s/n} presented frequency, signal duration, and amplitude modulation differences and in discrimination of interaural frequency and signal duration differences. In contrast, level discrimination ability was mostly unimpaired.

For all these discrimination tasks, also inner hair cell or auditory nerve damage could limit performance, without necessarily affecting audiometric thresholds (Weisz et al. 2006; Stone et al. 2008; Epp et al. 2012; Kumar et al. 2012). However, all the children referred to the participating clinics underwent intensive audiometric testing ruling out the auditory periphery was impaired (see “Testing the Integrity of the Peripheral Auditory System” section). Also, the BERA did not show any abnormal results in the clinical group, speaking in favor of an unimpaired auditory nerve. Additionally,

none of the patients complained about tinnitus, as was the case in some of the above-mentioned studies. Thus, a peripheral hearing loss caused by differentiations seems unlikely.

Despite the clinical relevance of APD, studies specifically investigating central auditory processing unrelated to speech functions are sparse, exacerbating a differentiation between impaired auditory processing and language-learning deficits. From our own clinical testing of patient groups suffering from distinct neurological diseases, we know of central auditory deficits as comorbid impairments, for example, in patients suffering from multiple sclerosis (MS) or auditory neuropathy (AN). The presently observed discrimination deficits in the children possibly bear more relation to deficits in MS and AN patients than those observed in connection with other neurodevelopmental disorders. This observation points to the need for targeted investigation of such problem cases and shall be briefly discussed using the example of interaural processing.

Interaural tests. The presently observed specific impairments of interaural temporal processing (explicitly not interaural level processing) in children are in accordance with findings in patients with MS (Häusler and Levine 1980; Häusler et al. 1983). Although MS patients and the presently investigated children with impairments in auditory processing do not correspond in age and in their general impairments, they may still show similarly reduced neuronal timing accuracy—MS causes a demyelination of axons resulting in imprecise transmission of action potentials (Häusler and Levine 1980; Häusler et al. 1983). High precision in action potential timing is also the basis for accurate processing of interaural time differences (ITD) (Finlayson and Caspary 1991; Batra et al. 1997; Tollin and Yin 2005) that might potentially be impaired in the presently investigated children with an auditory discrimination deficit. Similar impairments are also seen in patients suffering from AN (Starr et al. 1996; Rance et al. 1999). Other investigations also emphasize reduced speed of neuronal transmission causing deficits in temporal processing, for example, temporal resolution, detection of amplitude modulation, and temporal aspects of frequency discrimination (Rance et al. 2004; Zeng et al. 2005). Similar to the results observed here, AN patients in the Zeng et al. study failed in signal lateralization based on interaural time but not interaural intensity differences. Specifically focusing on children suffering from APD, Meister and co-workers reported a decline in binaural processing of temporal information on the basis of phase differences, as measured by masking level difference (MLD) (Meister et al. 2005). Referring to the fact that in the low-frequency range, frequency is coded (also) by phase-

locked neuronal responses (Tollin and Yin 2005; Dehmel et al. 2010), the deficits in interaural frequency discrimination shown in the present study speak for a reduced temporal processing acuity.

Dichotic_{s/n} tests. One key feature of the central auditory system is that the information conveyed through neuronal activity to either of the two auditory cortices is comprised of information processed on multiple levels and integrated from both ears (guinea pig, Rutkowski et al. 2000; cat, Reale and Brugge 1990; and macaque, Reser et al. 2000). Regarding signal processing, a functional dominance of the afferent pathway to the contralateral cortex was shown (guinea pig, Popelar et al. 1994; primate, Heffner and Heffner 1989; and human, Woldorff et al. 1999; Jäncke et al. 2002; Schönwiesner et al. 2007) that benefits a faster and stronger cortical activation of the contralateral ear's input (Hall and Goldstein 1968; Majkowski et al. 1971). Thus, in the dichotic_{s/n} condition, the activation generated in the auditory cortex of either hemisphere differs—in the cortex contralateral to the ear where the signals are presented the representation of the signal input predominates the noise input, while in the other cortex the respective weighting is reversed. Thus, this test design allows for distinct assessment of auditory cortical domains in both hemispheres (Biedermann et al. 2008). In the presently investigated children, there was no indication of a hemisphere-specific discrimination deficit in either auditory cortex. In the dichotic_{s/n} tests, such children showed elevated thresholds mostly for the parameters frequency, signal duration, and amplitude modulation. This is in agreement with earlier findings in APD children showing deficits in frequency discrimination and spectral processing (Vanniasagaram et al. 2004; Dawes et al. 2009; Sharma et al. 2009; Rosen et al. 2010) as well as in temporal processing (Dias et al. 2012).

Possible aetiologies for such auditory deficits are manifold. Some authors argue for a decelerated neuronal maturation (Jerger et al. 1988; Musiek et al. 1988; Jirsa and Clontz 1990). Reduced auditory skills could be caused by a slowed myelination (Musiek et al. 1985). However, improvements in the performance and respective alterations in electrophysiological correlates after a 2-week training period, reported by Jirsa (1992) can hardly be explained by rapid compensation of an incomplete maturation. Still, the facts are clear—discrimination deficits (deficits in frequency and duration discrimination) as seen in the presently investigated children could mostly be accounted for by temporal processing deficits provoked by reduced neuronal transmission efficiency.

Surely, there is the possibility that factors other than auditory skills may in part contribute to the

observed deficits in our clinical sample. For example, although testing sessions were distributed across several days, children in the clinical group had to complete more tests than children in the normative group. It cannot be fully ruled out that this more extensive testing of the clinical group could have been a source of bias, reflected as poorer test performance. The already very comprehensive and time-consuming testing did not allow for additional psychological evaluation of intelligence or reading and language skills both in the control and the APD children. However, the fact that participants in the control group were healthy, normally developing children from mainstream schools leads one to expect a limited range of variations in IQ and verbal skills. Our goal was to investigate children whose auditory and non-auditory skills represent a cross-section of the population at the respective ages. As a reassurance, we gathered additional information about the children by way of a questionnaire. In this respect, it is also important to point to several studies that report only little or no relation between auditory abilities and general intellectual capabilities (Kidd et al. 2007; Cameron and Dillon 2008; Sharma et al. 2009; Addis et al. 2010; Boscariol et al. 2011). Also, the same test repertoire was successfully used to study auditory performance in patients who—as a result of acquired brain lesions—suffered from cognitive deficits. These patients were able to master the tests and reached age-matched threshold values acquired from unimpaired subjects (Biedermann et al. 2008). However, although excluding children with a diagnosis of SLI or dyslexia from our clinical group, we cannot fully rule out the possibility that undiagnosed language or reading problems could have affected the results. Such possible influences could be considered in future studies.

The APD diagnosis as practiced today in Germany as well as in other countries has several limitations. Diagnostic test batteries can differ from clinic to clinic, as do protocols specifying the type and the number of failed individual tests required for the assessment of the APD syndrome. Critically, it is also the fact that normative data for some tests are out of date (e.g., 1951 for Mottier test) or restricted to only a few age groups, which is especially disadvantageous for testing children because of the noticeable developmental changes happening in the concerned age range. These limitations together with the inconsistent definition of APD are a source of confusion not only among clinicians and researchers but also among teachers, parents, and of course the concerned children. This unsatisfactory situation was confirmed by Wilson and Arnott (2013), who studied 150 children assessed for a possible APD. Depending on the criteria used, the rates of the diagnosis of (C)APD

ranged from 7.3 % when applying the strictest criteria to 96.0 % for the most lenient criteria. The authors concluded that the diagnosis APD hardly says anything about the actual deficits a child is suffering from, unless a reference is made about the criteria being used. These authors also recommended not using APD as a global label for any kind of listening problems.

CONCLUSION

In children suspected of APD, we observed a discrepancy between the results of audiological testing that are mostly based on the performance in speech understanding and reproduction, and tests which evaluate discrimination of acoustic parameters. The present results suggest that speech-based tests seem not to be sufficient to evaluate central auditory

processing in these children. The test inventory employed here successfully identifies children, whose deficits would have remained otherwise undiscovered.

ACKNOWLEDGMENTS

The authors want to thank Jürgen Baldauf who pioneered this investigation, but sadly and unexpectedly passed away during this study. Furthermore, we want to thank Karin Wenke and Katrin Dransfeld for supporting audiological data collection and allocation of diagnoses, and Ulrike Barth and Beate Günther for helping with the recruitment of control participants. Special thanks go to Gerd Joachim Dörrscheidt who implemented the threshold estimation algorithm and helped with the statistical analysis. We also thank Elizabeth Kelly for the proofreading of the manuscript.

APPENDIX

TABLE 7

Audiological data

Group	Child	Age/sex	BERA	CERA	Phonological differentiation	Dichotic speech	Short-term memory	Speech in noise	Localization
Center: Chemnitz									
noAPD	1	7/f	—	+	+	—	—	—	—
noAPD	2	8/f	—	+	—	+	—	—	—
noAPD	3	8/m	—	—	—	—	—	—	—
noAPD	4	8/m	—	+	—	—	—	—	—
noAPD	5	9/m	—	+	—	—	—	—	—
noAPD	6	10/f	—	—	+	—	—	—	—
noAPD	7	11/m	—	—	+	—	—	—	—
noAPD	8	12/m	—	—	+	—	—	—	—
noAPD	9	14/m	—	—	+	—	—	—	—
noAPD	10	17/f	—	—	—	—	—	—	—
APD	11	7/m	—	+	+	+	+	—	—
APD	12	8/f	—	+	+	—	—	+	—
APD	13	8/m	—	+	+	+	—	—	—
APD	14	8/m	—	+	+	+	—	—	—
APD	15	8/m	—	+	+	—	—	—	+
APD	16	8/m	—	+	+	—	—	+	—
APD	17	9/f	—	—	+	—	+	+	+
APD	18	9/m	—	+	+	+	+	—	—
APD	19	9/m	—	—	+	+	+	—	—
APD	20	9/m	—	+	+	—	+	—	—
APD	21	9/m	—	+	—	—	+	—	+
APD	22	9/m	—	+	+	+	—	—	+
APD	23	10/m	—	+	—	+	+	—	—
APD	24	11/m	—	+	+	—	—	—	+
APD	25	12/f	—	+	—	+	+	—	—
APD	26	12/m	—	+	+	+	+	—	—
Center: Goettingen									
noAPD	27	6/f	—	—	—	—	+	—	+
noAPD	28	6/f	—	—	—	—	+	—	—
noAPD	29	6/f	—	—	—	—	—	—	—
noAPD	30	6/f	—	—	—	—	+	—	—
noAPD	31	6/m	—	—	—	—	—	—	—

TABLE 7
(continued)

noAPD 32	6/m			+			+	—	—
noAPD 33	7/f			—	—		+	—	+
noAPD 34	7/f			—	—		+	—	—
noAPD 35	7/f				—		+	—	+
noAPD 36	7/m			—	—		+	—	—
noAPD 37	7/m			—	—		+	—	—
noAPD 38	7/m			—	—		—	—	—
noAPD 39 ^a	7/m								
noAPD 40	7/m				+		+	—	—
noAPD 41	8/m			—	—		—	+	—
noAPD 42	8/m			—	—		+	—	—
noAPD 43	8/m			+	—		+	—	—
noAPD 44	8/m			—	—		+	—	—
noAPD 45	9/m			+	—		+	—	—
noAPD 46	9/m			+	—		—	+	—
noAPD 47	9/m			—	—		+	—	—
noAPD 48	10/f			+	—		+	—	—
noAPD 49	11/f			—	—		—	+	—
noAPD 50	11/m			—	—		+	—	—
noAPD 51	11/m			—	—		+	—	—
noAPD 52	11/m			—	—		—	+	—
noAPD 53	11/m			—	—		+	—	—
noAPD 54	11/m			+	—		—	—	+
noAPD 55	11/m			—	—		+	+	—
noAPD 56	13/m			—	—		+	—	—
noAPD 57	14/m			+	—		+	—	—
APD 58	6/f			+	—		+	+	+
APD 59	6/f				+		+	+	—
APD 60	6/m			—	+		+	+	—
APD 61	6/m				+		+	—	+
APD 62	6/m				+		+	+	—
APD 63	6/m				+		+	+	—
APD 64	7/f			—	—		+	+	+
APD 65	7/m			+	—		+	—	+
APD 66	7/m			+	+		+	—	—
APD 67	8/m			+	—		+	+	+
APD 68	9/m			+	—		+	+	—
APD 69	9/m			+	—		+	+	—
APD 70	9/m			+	—		+	+	—
APD 71	10/f			+	—		+	—	+
APD 72	11/f			+	—		+	—	+
APD 73	12/m			+	—		+	+	—
APD 74	12/m			+	+		+	—	—
Center: Leipzig									
noAPD 75	6/m				—		+	—	
noAPD 76	10/m	—	—		—		—	—	
noAPD 77	17/f	—	—		—				—
noAPD 78	17/f	—	—		—			—	
APD 79	8/m	—			—		+	+	+
APD 80	8/m	—		—	—		+	+	+
APD 81	8/m	—	—	+	—		—	+	+
APD 82	9/m	—		+	—		—	+	+
APD 83	9/m	—		+	—		+	+	+
APD 84	11/m	—		+	—		+		+

Overview of results in audiological tests in the three different centers: — normal results, + abnormal results; Clinical standard for a positive APD diagnosis was abnormal results in three or more tests

^aData of one child was not available

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