Title: Development of central auditory processes in Polish children and adolescents at the age from 7 to 16 years

Author: Monika Lewandowska, Rafał Milner, Małgorzata Ganc, Elżbieta Włodarczyk, Joanna Dołżycka, Henryk Skarżyński

Citation style: Lewandowska Monika, Milner Rafał, Ganc Małgorzata, Włodarczyk Elżbieta, Dołżycka Joanna, Skarżyński Henryk. (2021). Development of central auditory processes in Polish children and adolescents at the age from 7 to 16 years. „Current Psychology" (10 March 2021), DOI:10.1007/s12144-021-01540-x

Current Psychology
https://doi.org/10.1007/s12144-021-01540-x

Development of central auditory processes in Polish children and adolescents at the age from 7 to 16 years

Monika Lewandowska[1,2] · Rafał Milner[2,3] · Małgorzata Ganc[3] · Elżbieta Włodarczyk[4] · Joanna Dołżycka[5] · Henryk Skarżyński[6]

Accepted: 23 February 2021

Abstract
There are discrepancies in the literature regarding the course of central auditory processes (CAP) maturation in typically developing children and adolescents. The purpose of the study was to provide an overview of age – related improvement in CAP in Polish primary and secondary school students aged 7–16 years. 180 children/adolescents, subdivided into 9 age categories, and 20 adults (aged 18–24 years) performed the Dichotic Digit Test (DDT), Duration Pattern Test (DPT), Frequency Pattern Test (FPT), Gap Detection Test (GDT) and adaptive Speech-in-Noise (aSpN). The 12-year-olds was retested after w week. We found the age effects only for the DDT, DPT and FPT. In the right ear DDT the 7-year-olds performed more poorly than all groups ≥12. In the left ear DDT both 7- and 8-year-olds achieved less correct responses compared with the 13-, 14-, 15-year-olds and with the adults. The right ear advantage was greater in the 7-year-olds than in the 15-year-olds and adult group. At the age of 7 there was lower DPT and FPT scores than in all participants ≥13 whereas the 8-year-olds obtained less correct responses in the FPT than all age categories ≥12. Almost all groups (except for the 7-year-olds) performed better in the DPT than FPT. The test-retest reliability for all tests was satisfactory. The study demonstrated that different CAP have their own patterns of improvement with age and some of them are specific for the Polish population. The psychoacoustic battery may be useful in screening for CAP disorders in Poland.

Keywords Central auditory processes · Central auditory nervous system · Screening auditory tests · Auditory processing development

Introduction

Central auditory processes (CAP) allow to interpret information that comes through listening and include several functions: sound localization, auditory discrimination, time-related aspects of audition (temporal resolution, integration, ordering and masking, pattern recognition), understanding of degraded speech (filtered, time-compressed) or speech presented against the background noise, as well as performance of competing acoustic signals, e.g. during a dichotic listening task (Association (ASHA), 2005; Association (BSA), 2018; Musiek, Baran, Bellis, & Chermak, 2010). When at least two CAP are disturbed (or only one, but seriously), and there is no hearing loss, Central Auditory Processing Disorder (CAPD) is recognized (Association (ASHA), 2005; DeBonis, 2015; Iliadou et al., 2017). CAPD affects 2–3% of children population (Chermak & Musiek, 1997) and may be caused by the brain damage of different etiologies (Bamiou, 2001; Musiek & Weihing, 2011). Behavioral characteristics of CAPD comprise poor language and/or literacy skills, difficulty in localization of the sound

✉ Monika Lewandowska
mlewando@umk.pl

1 Bioimaging Research Center, Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland

2 Faculty of Philosophy and Social Sciences, Institute of Psychology, Nicolaus Copernicus University, Fosa Staromiejska 1a Str., 87-100 Torun, Poland

3 Experimental Audiology Department, World Hearing Center /Institute of Physiology and Pathology of Hearing, Warsaw/ Kajetany, Poland

4 Audiology and Phoniatrics Clinic, World Hearing Center/Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland

5 Institute of Linguistics, University of Silesia in Katowice, Katowice, Poland

6 World Hearing Center/Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland

Published online: 10 March 2021

source, inattention and/or a tendency to be distracted. Impaired CAP co-occur with various developmental disorders including dyslexia (Dawes & Bishop, 2010; King, Lombardino, Crandell, & Leonard, 2003; Sharma, Purdy, & Kelly, 2009; Zaidan & Baran, 2013; Ziegler, Pech-Georgel, George, & Lorenzi, 2009), SLI (Vandewalle, Boets, Ghesquière, & Zink, 2012), ADHD (Riccio, Hynd, Cohen, Hall, & Molt, 1994) or autism (O'Connor, 2012).

The CAP tests performance continues to increase throughout childhood, up to adolescence in some cases (Cameron, Dillon, & Newall, 2006; Cameron, Glyde, Dillon, Whitfield, & Seymour, 2016; do Amaral, Martins, & Colella-Santos, 2013; Eggermont & Ponton, 2003; Fitzroy et al., 2015; Irwin, Ball, Kay, Stillman, & Rosser, 1985; Keith, 2000; Krizman et al., 2015; Ludwig et al., 2014; McDermott et al., 2016; Moav, Nevo, & Banai, 2009; Moore, Cowan, Riley, Edmondson-Jones, & Ferguson, 2011; Neijenhuis, Snik, Priester, van Kordenoordt, & van den Broek, 2002; Schochat & Musiek, 2006; Stollman, van Velzen, Simkens, Snik, & van den Broek, 2004; Sussman, Wong, Horváth, Winkler, & Wang, 2007; Yathiraj & Vanaja, 2015). This improvement within the age range of our interest, i.e. from 7 to 16 years, is attributed to the Central Auditory Nervous System (CANS) maturation (Krizman et al., 2015; Ludwig et al., 2014) but also to the development of non-auditory functions (attention, language) which practically cannot be separated from CAP measured by behavioral tests (Murphy, Zachi, Roque, Ventura, & Schochat, 2014; Riccio, Cohen, Garrison, & Smith, 2005; Stavrinos, Iliadou, Edwards, Sirimanna, & Bamiou, 2018). The Auditory Brain Responses (ABRs), i.e. electrical potentials reflecting the electrophysiological activity of the brainstem, and the Auditory Evoked Potentials (AEPs) which represent summed postsynaptic potentials that arise from activity across different sources in the auditory, are thought to investigate CANS maturation more objectively compared to the behavioral tasks system (Picton et al., 1999; Ponton, Eggermont, Khosla, Kwong, & Don, 2002; Ponton, Eggermont, Kwong, & Don, 2000). ABRs appear adult-like by about age 2 and from 5 to 11 years overshoot for their parameters were observed, with earlier latencies and greater amplitudes than the adult value (Skoe, Krizman, Anderson, & Kraus, 2015). The AEPs components (P1, N1, P2 and N2) also reflect the CANS development up to early adulthood through changes in their latency, amplitude and morphology (Fitzroy et al., 2015; Ponton et al., 2000; Ponton, Don, Eggermont, Waring, & Masuda, 1996; Sharma, Kraus, McGee, & Nicol, 1997; Sussman, Steinschneider, Gumenyuk, Grushko, & Lawson, 2008). Therefore, the ABRs and AEPs could be considered as biomarkers of the CANS maturation, however, their clinical utility is rather limited since multi-channel EEG recording is not available in many audiological centers, the use of these methods raises the costs of CAP assessment and involves much time and effort (Musiek et al., 2010).

The brain structures responsible for CAP (both those belonging to the CANS and outside it) have shown their own dynamics of anatomical and functional changes from early childhood up to adulthood. Overall, CAP that depend upon the brainstem (e.g. auditory gap detection and understanding of speech-in-noise) will develop early (by the age of 2–3 years, according to most findings, e.g. Eggermont, Ponton, Coupland, & Winkelaar, 1991; Ponton, Eggermont, Coupland, & Winkelaar, 1992), however, maturational plasticity of the brainstem was also found between 3 and 18 years of age (Johnson, Nicol, Zecker, & Kraus, 2008; Krizman et al., 2015; Skoe et al., 2015). In contrast, those auditory functions that rely on efficient interhemispheric communication (e.g. dichotic listening or auditory pattern recognition) reach the adult-like level much later. The myelination of auditory cortex continues into adolescence (Paus et al., 1999) and this process for the corpus callosum lasts even up to early adulthood (Luders, Thompson, & Toga, 2010; Pujol, Vendrell, Junqué, Martí-Vilalta, & Capdevila, 1993). Therefore, it is reasonable to expect that the rate of improvement in psychoacoustic tests would be different dependently on what auditory function is being assessed.

Despite that the course of age-related changes in CAP reflects the CANS maturational process that appears to be independent of linguistic and cultural background of the person whose auditory performance is being examined, the dynamics of improvement, observed in the psychoacoustic tests, during childhood, varies from one to another country (e.g. Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Romero-Díaz, Peñaloza-López, García-Pedroza, Pérez, & Castro Camacho, 2011; Stollman et al., 2004). This may result from both a great diversity of procedures/stimuli used to examine particular process (many authors developed their own tasks and batteries, e.g. Cameron et al., 2006; Cameron & Dillon, 2008; Fuente & McPherson, 2006; Mukari, Keith, Tharpe, & Johnson, 2006) and different home languages of children referred for evaluation (Bao et al., 2013; Dawes & Bishop, 2007; Marriage, King, Briggs, & Lutman, 2001; Woods, Peña, & Martin, 2004). Sometimes even an accent (Dawes & Bishop, 2007; Loo, Bamiou, & Rosen, 2013) or learning a second language (Weiss & Dempsey, 2008) may affect the outcomes. Therefore, to ensure the clinical utility of psychoacoustic tests, the baseline population scores should be determined for the same population from which the child at risk of CAPD comes from.

The aim of the present study is twofold: 1) to determine the course of age – related changes in behavioral CAP tests performance in Polish children and adolescents aged from 7 to 16 years, as well as 2) to provide the reference values and evaluate the clinical validity of the auditory processing battery proposed. To our knowledge not many papers have focused on the development in more than two processes (Mattsson et al., 2018; McDermott et al., 2016; Moore et al., 2011; Neijenhuis et al., 2002) and the maturation effect has been rarely investigated in children older than 11–12 years (Fitzroy et al., 2015; Krizman et al., 2015; Moav et al., 2009).

The current work complements, to the some extent, our previous paper (Włodarczyk, Szkiełkowska, Skarżyński, Miaśkiewicz, & Skarżyński, 2019) presenting the reference values for selected psychoacoustic tests (those that require recognition of duration and frequency patterns, dichotic listening or understanding of time-compressed speech) for children aged 7–10 years. The CAP development was not the main object of interest in this paper, however, the comparisons of psychoacoustic tests scores revealed some significant age effects. Specifically, the 7-year-olds performed more poorly than the 9- and 10-year-olds in the duration pattern test whereas both 7- and 8-year olds were worse than the older age groups in the dichotic listening and time-compressed speech tasks. In the latter two tests the 7- and 8-year-old as well as the 9- and 10-year-old groups were not significantly different. The age effect for the frequency patterns was not determined due to a high variability of the outcomes.

Since it has been repeatedly suggested that the CANS maturation is not finished until the age of 12, in the present study we intend to investigate how auditory performance of typically developing Polish children changes up to the age of 16 (Fitzroy et al., 2015; Krizman et al., 2015; Ludwig et al., 2014). The psychoacoustic battery, used by Włodarczyk et al. (2019), was supplemented with the test measuring temporal resolution which should be included to screening for CAPD (DeBonis, 2015; Musiek et al., 2010) due to its sensitivity for the brainstem lesions (Musiek & Chermak, 2015). Furthermore, the compressed speech test, used in the previous study, was replaced with the speech-in-noise because the latter has been especially recommended to be administered as a part of the CAP assessment, right after a child history, medical examination and pure tone audiometry (Association (BSA), 2018).

We hypothesized that the performance on the dichotic listening and auditory pattern tests would increase gradually with age up to 16 years. Both types of tasks involve the CANS structures (the auditory cortex and the corpus callosum which mature into early adulthood, 2) the outcomes of these CAP tests are strongly affected by non-auditory, cognitive functions such as attention or working memory (both of them require keeping in mind the sequences of acoustic elements for a while before they are reported) with their own developmental course until the age of 16 (Cowan, 2016; Gomes, Molholm, Christodoulou, Ritter, & Cowan, 2000; Karns, Isbell, Giuliano, & Neville, 2015).

Naturally, the development of dichotic listening and auditory pattern recognition in children has been already demonstrated in many countries (Dekerle & Meunier, 2018; Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002; Schochat & Musiek, 2006; Stollman et al., 2004). However, home language of children and adolescents, participated in our study, is different from all of them which allows us to believe that the dynamics of age-related changes in these tests and the moments when the scores reach the adult-like level are also unique for the Polish population. This prediction refers to the specificity of material used to investigate dichotic listening. For example, in contrast to the English version of the test where all digits are mono-syllabic, in Polish more than a half of digits from 0 to 9 is bi-syllabic which requires from the listener to report longer sequences, with a higher cognitive effort. Furthermore both dichotic digit pairs and nonverbal auditory patterns are requested to be reported orally. In the dichotic listening task the way of responding probably would not be as important as in case of the auditory pattern tests where the listener is asked to assign some labels to each type of the sequence (e.g. "*long – short – long*" or "*high – low – high*". Especially young children may find difficult to learn naming the tones as "*high*" or "*low*" (according to our clinical experience the "*thin*" or "*thick*" labels are much more natural and easier to remember). Therefore, we hypothesized that both specificity of verbal stimuli and the differences in the way of formulating responses in these tests would significantly affect the course of age-related changes in dichotic listening and auditory pattern recognition tests performance across the age range considered.

In the dichotic listening task the right ear advantage (REA), which represents the left hemispheric dominance for language (Hugdahl, Andersson, AsbjØrnsen, & Dalen, 1990; Kimura, 1961a, 1961b, 1967), are most likely observed, especially in younger listeners (Kimura 1961;Mattsson et al., 2018 ; Rosenberg, 2011). Inconsistent results are reported in the literature concerning how the REA changes with age (Mattsson et al., 2018; Moncrieff, 2011; Mukari et al., 2006; Rosenberg, 2011; Westerhausen et al., 2011). Westerhausen et al. (2011) found parallel differences in the REA for the dichotic syllables task and thickness of the isthmus (a posterior part of the corpus callosum) between the 6- and 8-year-olds. Moncrieff (2011) documented the REA presence in about 60% of children aged 5–7 years, 7 5% of 8- to 10-year-olds and 70% of 10- to 12-year-olds. Mukari et al. (2006) have shown significant increase of REA (for the dichotic digit test in Malay language) only from the age of 6 to 7 (3% to 7%) whereas in all older groups (up to 11 years) these values were comparable. The REA decrease from about 12–13% in children, aged 6–7 years, to about 6% in the 11–12-year-olds was also found (Mattsson et al., 2018; Rosenberg, 2011). The aforementioned discrepancies in the course of age – related REA encouraged us to investigate this effect in Polish population.

Previous findings by Włodarczyk et al. (2019) made us also wonder if Polish children indeed recognize the sequences of sounds that are different in duration better than the frequency patterns (which was neither reported nor discussed in this paper). This observation is not exactly congruent with the other studies where children either outperformed the frequency over duration patterns (McDermott et al., 2016), or the results of both these tests are comparable (Mattsson et al., 2018; Neijenhuis et al., 2002; Romero-Díaz et al., 2011; Stollman et al., 2004). Musiek (1994) suggested that the frequency and duration patterns tests measure different abilities. The DPT uses only one frequency which makes it relatively unaffected by the cochlear damage but, instead, it is thought to be more sensitive to the CANS lesions compared to the FPT (Musiek, Baran, & Pinheiro, 1990; Scharlock, Neff, & Strominger, 1965). Although these tests are very similar, it is reasonable to expect that there would be different course of their improvement with age in children.

We hypothesized that for Polish children the frequency patterns would be more difficult to recognize than those formed by the tones of different durations possibly due to all the following factors combined: 1) specific intonation patterns in Polish language: we do not have the "*high – low – high*" or "*low – high – low*" nuclear tones which may result in a greater difficulty in recognizing the frequency compared with the duration patterns; 2) inadequate music education in Polish schools and 3) a tendency to use different that "*high*" and "*low*" labels for the tones while reporting the sound sequences, observed especially in younger children.

Existing evidence on age-related changes in gap detection performance in children and adolescents are inconsistent. The vast majority of studies have revealed that the adult-like level in these tests is reached by the age of 7 years (do Amaral et al., 2013; Ismaail, Shalaby, & Ibraheem, 2019; Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Shinn, Chermak, & Musiek, 2009) independently of the procedure applied (Chermak & Lee, 2005). However, an improvement in detecting gaps in noise up to 10–11 years (Buss, Porter, Hall, & Grose, 2017; Irwin et al., 1985) or in the 7–10 age range with a greater variability of the results in younger than older kids, has been also demonstrated (Lister et al., 2011). In the present study we predicted that our version of gap detection test would produce relatively stable scores over the age range considered. However, we did not completely rule out a possibility that there would be some improvement among children older than 7 years, first because an ability to detect gaps in noise relies on the auditory brainstem function which, according to some findings, changes even until early adulthood (Krizman et al., 2015; Skoe et al., 2015) and, second, impaired performance on this test was linked to dysfunction of the auditory cortex (Efron et al., 1985) which could be not completely matured even in adolescents (Paus et al., 1999).

We also expected that there would be no considerable age-related improvement between 7 and 16 years in the speech-in-noise intelligibility test. Our prediction was based on previous studies demonstrating stable results in this test from the age of 7 (Keith, 2000; Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002; Stollman et al., 2004; Wilson, Farmer, Gandhi, Shelburne, & Weaver, 2010). As was the case with the auditory gap detection, we developed our version of speech-in-noise test, with Polish mono-syllabic words presented against a multitalker babble. Since the unique verbal material was used here, the reference values for particular age groups in children and adolescents are needed.

It is also thought that poor temporal resolution contributes to reduced speech understanding in noise (Stuart et al., 2006). When speech is exposed against background sounds, the rapid temporal changes of them mix with those inherent in the speech signal. As a result, temporal cues in speech may be distorted (Cooke, 2006; Lutman, 1991). Therefore, we expected that in our study there would be either a parallel improvement in the speech-in-noise and gap detection tests or in both of them the values would be stable across the age range considered.

To verify the above hypotheses children in the 7–16 age range were divided into 9 age categories and their outcomes in particular CAP tests were compared with each other and also with the results achieved by young adults (to determine when each auditory process reaches the adult level). The reference values for Polish battery were provided as well as the reliability measures of the psychoacoustic tests in the group of 12-year-olds.

Method

Subjects

A group of 180 normally developing children and adolescents (92 girls and 88 boys, mean age = 11,43 ± 2,62 years, age range: 7–15,9 years), recruited from 3 primary and 2 secondary schools in Toruń (< 200,000 inhabitants), Warsaw (< 2,000,000) and in the rural areas in the vicinity of Warsaw, as well as 20 young adults (11 women and 9 men, mean age = 20,5 ± 1,8 year, age range: 18–24 years) who responded to an advertisement in the local press, participated in the study. All participants were native speakers in Polish.

Children were classified into nine age categories (see: Table 1). All subjects had normal hearing in both ears with pure tones thresholds ≤15 dB HL at the octave frequencies from 250 to 8000 Hz and type A tympanograms. They were all right-handed (Oldfield, 1971) and had intellectual abilities within the normal range.[1] Other information was provided by parents/caregivers and teachers of the children and adolescents as well as by the adults themselves. All subjects had no history of neuropsychiatric disorders or head trauma and did not take any medications affecting the Central Nervous System. Children and adolescents were varied in terms of socioeconomic status, attended school regularly, were in a good health, and did not have any recognized developmental

[1] Each child performed the Raven matrices test showing a normal or above normal intellectual abilities. Specific results of the test were not reported because children were assessed at school and parents of many of them did not agree to provide the exact scores.

Table 1 Subjects divided into age groups

	Children and young people									Total	Adults	Total
Age (years – years; months)	7–7;11	8–8;11	9–9;11	10–10;11	11–11;11	12–12;11	13–13;11	14–14;11	15–15;11		18–23;11	
Females	11	10	10	9	10	10	12	10	10	92	11	103
Males	9	10	10	11	10	10	8	10	10	88	9	97
Total	20	20	20	20	20	20	20	20	20	180	20	200

disorder (e.g. dyslexia, SLI, ADD/ADHD, ASD) or a risk of it. Participants who received a formal music education, which might have affected the CAP tests performance, were excluded from the study.

Ethics Statement

Prior to testing parents/caregivers of the children/adolescents and the adult subjects provided a written informed consent to participation in the project. The study was approved by the ethics committee of the Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland, and is in accordance with the Declaration of Helsinki for research on humans.

The authors were not provided with the data enabling the identification of the subjects. The study was conducted by 3 persons, trained in CAP evaluation with the use of the psychoacoustic tests in children, and under appropriate acoustic conditions.

Procedures

Children and adolescents were tested individually in quiet rooms in their school buildings whereas tasks for adults were conducted in the laboratories of the Institute of Physiology and Pathology of Hearing, Warsaw/Kajetany, Poland. Three experimenters, trained in the area of CAP assessment, collected the data and they were instructed to administer and score the tests in the same manner. The CAP tests, applied in this study, were developed as a result of scientific cooperation between the World Hearing Center, Institute of Physiology and Pathology of Hearing (Poland) and the Department of Communication Disorder Brigham Young University (USA). The tests were administered using a Notebook HP Probook 4510S computer running Microsoft XP Professional. Auditory stimuli were presented via headphones (Sennheiser HDA 200) using a Creative SB1–100 sound card. Each of the tests was preceded by a training session to familiarize subjects with the procedures.

A set of tests referring to the following aspects of audition were administered: dichotic listening (Dichotic Digit Test, DDT), temporal processing (Duration Pattern Test, DPT, Frequency Pattern Test, FPT and Gap Detection Test, GDT) as well as performance with degraded speech (adaptive Speech-in-Noise, aSpN). The pure tone audiometry and CAP evaluation were performed during a single ca. 1-h session (with short breaks). The order of CAP tests was counterbalanced across subjects.

In order to provide some measures of test-retest reliability of our CAP battery, the group of 12-year-olds ($n = 20$) was tested twice, in about a week apart (mean = 7.25 days ±1.86).

Dichotic Listening

During the DDT (Musiek, 1983) children were presented with a sequence of two different digits (from 1 through 10) in the left ear at the same time as they were given a sequence of two different digits in the right ear and they were asked to repeat the digits from both ears. There were 40 digit pairs (20 pairs *per* the ear). The stimuli were presented at 60 dB HL. Percentages of correctly reported digits, both separately from the left and right ears as well as the difference in performance between the right and the left ear in DDT (the right ear advantage, REA[2]) was calculated.

Temporal Processing

The FPT (Pinheiro & Ptacek, 1971) consisted of 40 triplets of 180-ms sine wave tones (rise/decay time of 10 ms) of either low (880 Hz) or high (1122 Hz) frequency presented binaurally at 60 dB HL. Each triplet consisted of one, two or three tones of low or high frequency with an inter-tone-interval (ITI) of 200 ms. The task was to orally report the order of the tones, e.g. "*high – low – high*". The sequences within a test were presented in pseudo-random order. The percentage of correct responses were analyzed.

The DPT (Musiek et al., 1990) used 40 binaural 3-element-sequences of 1000-Hz sine wave tones (rise/decay time of 10 ms) differing in duration and presented with an ITI of 300 ms. The tones were either short (250 ms) or long (500 ms) and were presented at 60 dB HL. Subjects were asked to repeat the order of the tones within a sequence (e.g. /short/ - /long/ - /long/). The percentage of correct responses was again analyzed.

[2] REA = (%of correct responses in the right ear − % of correct responses in the left ear)/(%of correct responses in the right ear + % of correct responses in the left ear)

The GDT measured the shortest length of a silent gap embedded in white noise required for perceiving and reporting the gap. The stimulus was 500-ms white noise presented to both ears at 50 dB HL. An adaptive procedure was applied searching for the length at which there was a 50% chance of detecting the noise with a gap and 50% of a noise without a gap (Leek, 2001). The task was to press a button in response to a gap embedded in noise. In this test the minimal gap duration was determined in a two-stage procedure. In the first stage stimuli with varying gap durations were presented. The initial gap duration was 10 ms and it decreased or increased by half of its length depending on the correctness of the subject's response. This part of the test was continued until a subject failed three times to detect a gap of the same duration. This gap duration was then applied in the test proper and it was adjusted according to the individual subject's performance, i.e. it increased by 2-ms following a *false alarm* (a button press in the absence of a noise with a gap) or a *miss* (no reaction to a gap stimulus) and decreased by 2 ms after a *hit* (a correct gap detection). The test was terminated after 7 reversals. A reversal was defined as a *hit* followed by a *miss* (or a *false alarm*) or a *miss* (or *false alarm*) followed by a *hit*. The average of the 5 most difficult reversals gave the minimum gap duration.

Speech-in-Noise

In the aSpN single-syllable Polish words (Harris, Nielson, McPherson, Skarzynski, & Eggett, 2004) were successively presented against the background of 16-talker babble speech. The task was to repeat the words. The words were delivered to both ears using different signal-to-noise ratios (SNRs). The initial (maximum) SNR was 9 dB and the minimum was −15 dB. Negative SNRs indicate that the background noise is louder than the target word and positive values correspond to a situation where a target word is louder than the background noise. An adaptive procedure was applied in which, initially, the SNR decreased by 4 dB after each correct response. From the moment a subject did not respond correctly for the first time, the SNR increased by 2 dB following each incorrect word and decreased by 2 dB following each correctly repeated word. aSpN measures the minimum SNR required to correctly recognize words 50% of the time. The calculations were performed in line with the Wilson and McArdle approach (Wilson & Burks, 2005) and were based on the 5 most difficult reversals, i.e. correctly repeated words followed by an incorrect one (or lack of a response) or incorrect answers followed by a correct one. The test concluded after 7 reversals.

Statistical Analysis

The statistical analyses were performed with SPSS 27.0 software (SPSS Inc., Chicago, Illinois) and R (R Core Team, 2020). To check for normality of variables distributions in each group the Shapiro–Wilk's test was conducted and Levene's test was used to verify whether the variances of age groups were homogeneous. The results of the GDT and aSpN and also the REA index showed abnormal distributions which might be caused by too much persons with similar scores. In case of these variables the non-parametric Dunn test and the Kruskal-Wallis H tests were used for comparisons between two or more age categories, respectively. The results were corrected for multiple comparisons (Bonferroni).

Since the distributions were normal but the variances of most variables in particular age categories remained heterogeneous, we used the Welch one-way ANOVA which is recommended when the assumption of equal variances in comparing groups is not valid. The *post-hoc* comparisons were performed with the use of Games-Howell test that also does not assume equal variances between compared groups. Finally, bootstrapped paired t tests ($n = 1000$) were applied to determine the differences in the DDT scores between the right and left ears as well as between the DPT and FPT performance in each age category.

Test–retest reliability for each of the CAP tests was examined by the intra-class correlation coefficient (ICC) (McGraw & Wong, 1996) for a group of 12-year-olds retested after ca. 7 days (mean = 7.25 days ±1.86). ICC values and their 95% confident intervals were based on a mean-rating (k = 2), consistency, 2-way random-effects model. For a categorical description of the level of reliability, we followed the suggestions by Koo and Li (Koo & Li, 2016): ICC > 0,9 indicates "excellent" reliability, ICC between 0,75 and 0,9 "good" reliability, ICC between 0,5 and 0,75 indicate "moderate" reliability and the values <0,5 correspond to "poor" reliability. Additionally, since the distributions in all tests in this group did not significantly deviate from normality, the series of bootstrapped paired t-tests ($n = 1000$) were used to check for the learning effects.

Results

Age Effects

Significant age effects were found for the right ($F(9, 77{,}34) = 6{,}39$, $p < 0{,}01$) and left ear ($F(9, 77{,}29) = 11{,}74$, $p < 0{,}01$) in the DDT as well as for the DPT ($F(9, 77{,}15) = 6{,}76$, $p < 0{,}01$) and FPT ($F(9, 77{,}05) = 10{,}9$, $p < 0{,}01$). The age categories were also different in terms of the REA index, calculated on the basis of the DDT results ($\chi^2 = 34{,}48$, $p < 0{,}01$). The intergroup differences in the GDT ($\chi^2 = 11{,}95$, $p = 0{,}22$) and aSpN ($\chi^2 = 11{,}69$, $p = 0{,}23$) scores were not statistically relevant.

The age-related changes in particular CAP tests performance are shown in Fig. 1. Table 2 contains the descriptive statistics for each age group whereas the detailed results of *post-hoc* comparisons are shown in Tables S1-S5.

In the DDT (right ear) the 7-year-olds ($\bar{x}$ = 77,1% ± 9,2) performed more poorly than the 12-year-olds ($\bar{x}$ = 89,3% ± 6,7; t (1, 35) = 4,78, *p* = 0,05), 13-year-olds ($\bar{x}$ = 90,3% ± 7,4; t (1, 36) = 4,99, *p* = 0,03) and the adults ($\bar{x}$ = 91,7% ± 5,1; t(1, 30) = 6,17, *p* < 0,01). There was also a tendency (t (1, 36) = 4,56, p = 0,09) towards lower scores in this test at the age of 7 years compared with the 15-year-olds ($\bar{x}$ = 89,1% ± 7,4).

In the DDT (left ear) the 7-year-olds achieved lower scores ($\bar{x}$ = 55,5% ± 17,5) compared with the 13-year-olds ($\bar{x}$ = 81,8% ± 11,4; t (1, 33) = 5,67, *p* < 0,01), 14-year-olds ($\bar{x}$ = 80,1% ± 12,3; t (1, 34) = 5,19, *p* = 0,02), 15-year-olds ($\bar{x}$ = 83,1% ± 7,9; t (1, 27) = 6,47, *p* < 0,01) and the adult group ($\bar{x}$ = 85,7% ± 5,7; t (1, 23) = 7,41, p < 0,01). Furthermore, the 8-year-olds obtained less correct responses in this test ($\bar{x}$ = 60,1% ± 13,2) than the 13-year-olds (t (1, 37) = 5,55, p < 0,01), 14-year-olds (t (1, 38) = 4,97, *p* = 0,03), 15-year-olds (t (1, 31) = 6,67, *p* < 0,01) and the adults (t (1, 26) = 7,96, p < 0,01). The 9-year-olds showed a trend (t (1, 25) = 4,9, *p* = 0,07) towards poorer left ear DDT performance ($\bar{x}$ = 69% ± 14,2) compared with the adult group.

Considering the REA index significant differences were found for the following comparisons: 7-year-olds ($\tilde{x}$ = 15,79, range: −1,69–55) vs. 15-year-olds ($\tilde{x}$ = 3,72, range: −3,03 – 11,48, z = 3,73, *p* = 0,01) and the 7-year-olds vs. adults ($\tilde{x}$ = 1,95, range: 0–12,39, z = 3,95, *p* < 0,01). There was also a tendency (z = 3,07, *p* = 0,09) towards a higher REA at the age of 7 vs. 13 years ($\tilde{x}$ = 4,58, range: −5,56 – 22,81). The 8-year-olds demonstrated a higher REA value ($\tilde{x}$ = 14,55, range: −14,29 – 13,33) compared with the 15-year-olds (z = 3,65, *p* = 0,01) and the adults (z = 3,87, *p* < 0,01).

In the DPT the 7-year-olds had less correct responses ($\bar{x}$ = 60,5% ± 16) than the 13-year-olds ($\bar{x}$ = 82,1% ± 8; t (1, 28) = 5,4, *p* = 0,02), 14-year-olds ($\bar{x}$ = 83,9% ± 12; t (1, 35) = 5,23, *p* = 0,01), 15-year-olds ($\bar{x}$ = 86,6% ± 9,4; t (1, 31) = 6,3, *p* < 0,01) and the adults ($\bar{x}$ = 88,3 ± 8,2; t (1, 28) = 6,91, *p* < 0,01). There was also a tendency towards worse performance in this test in the 7-year-olds relative to the 10-year-olds ($\bar{x}$ = 81,5% ± 11,7, t (1, 35) = 4,74, p = 0,06) and 11-year-olds ($\bar{x}$ = 80,9% ± 10,3, t (1, 33) = 4,8, p = 0,06).

In the FPT the 7-year-olds performed more poorly ($\bar{x}$ = 52,9% ± 17,6) than the 13-year-olds ($\bar{x}$ = 78,3% ± 9,6; t (1, 29) = 5,65, p = 0,01), 15-year-olds ($\bar{x}$ = 79,6% ± 13,1; t (1, 35) = 5,44, p = 0,01) and the adults ($\bar{x}$ = 82,6% ± 7,1; t (1, 25) = 6,98, p < 0,01). Additionally, at the age of 8 the FPT scores were decreased ($\bar{x}$ = 52,7% ± 14,8) compared with the results in children at the age of 12 ($\bar{x}$ = 73% ± 9,3; t (1, 32) = 5,2, p = 0,02), 13 (t (1, 33) = 6,49, p < 0,01), 14 ($\bar{x}$ = 75,4% ± 14,8; t (1, 38) = 4,86, *p* = 0,03) and 15 (t (1, 37) = 6,1, p < 0,01) and in the adults (t (1, 27) = 8,15, p < 0,01).

Ear Effect in the DDT

There was significantly higher percentage of correct responses for the right ear compared to the left ear in all analyzed age categories (Fig. 1, Table 3).

Duration Vs. Frequency Patterns

In almost all age categories, except for 7-year olds, the duration patterns were recognized more correctly than frequency patterns (see: Fig. 1 and Table 3).

Test-Retest Reliability

The intra-class correlation coefficients (ICC) for particular psychoacoustic tests as well as the test-retest differences between the first and second CAP evaluation, are presented in Table 4. The reliability of individual performance between the first and second test session for the 12-year-old children was considered as "good" for the DPT and DDT (left ear) and "moderate" for the remaining CAP tests. Only the GDT performance significantly (p = 0,03) improved after about a week period of time.

Discussion

In the present study we sought to determine the dynamics of changes in performance of psychoacoustic battery in typically developing Polish-speaking children and adolescents, aged from 7 to about 16 years. Since we used our own versions of the tests, we considered important to know how their outcomes change over time. The current study complements, to some extent, our previous findings (Włodarczyk et al., 2019) with: 1) the results of two psychoacoustic tests (measuring temporal resolution and speech-in-noise understanding) recommended for CAPD evaluation (Association (ASHA), 2005; DeBonis, 2015; Musiek et al., 2010), 2) the reference values for the age groups over 10 years and 3) the measures of CAP test-retest reliability.

Summary Results

We found significant age effects for the DDT, DPT and FPT but not for the aSpN and GDT performance (Fig. 1). The comparisons between particular age categories indicate that the 7-, 8-, 9-,10- and 11-year-old children were indistinguishable in terms of the right ear DDT results and only the 7-year-olds performed worse in this test compared with all groups above 11 (Table S1). The DDT scores for the left ear were lower in both 7- and 8-year-olds than in the age categories above 10 (or above 12, after taking account the correction for multiple comparisons). The 9-, 10-, 11- and 12-year-olds

Table 2 Means (M), medians (Me), standard deviations (SD) and minimum and maximum (min-max) values of central auditory processing tests scores in each age group

Age group	DDT (%)			DPT (%)	FPT (%)	GDT (ms)	aSpN (dB)
	R	L	REA				
7 yrs							
M	77,1	55,5	18,2	60,5	52,9	3,9	0,3
Me	78,8	60	15,8	60	52,5	3,7	0,5
SD	9,2	17,5	15,2	16	17,6	1,4	1,3
min-max	55–90	22,5-87,5	-1,7–55	27,5–90	22,5–90	1,9-8,2	−2-3
8 yrs							
M	80,1	60,1	14,5	67,7	52,7	3,3	0,1
Me	83,8	58,8	14,6	68	51	3,2	0
SD	13,5	13,2	12,3	21,6	14,8	0,8	1,3
min-max	52,5-97,5	32,5 −87,5	-14,3–33,3	22–100	28–85	1,8-5,1	-2-2
9 yrs							
M	81,3	69	8,7	73,8	63,3	3,5	0,3
Me	82,5	68,8	6,1	73,8	65	3,4	0,5
SD	10	14,2	9,9	18,1	20,1	0,7	1,2
min-max	65–100	40–95	-6,9-27,3	37,5-97,5	25–97,5	2,6-5,5	-2-2
10 yrs							
M	86,8	71,9	10	81,5	61,1	3,3	0,1
Me	87,5	71,3	10,4	83,8	62,5	3	0
SD	9,1	14,9	13	11,7	29,5	0,6	1,6
min-max	65–100	37,5–100	-8,5–42,3	52–95	20–100	2,5-4,9	−3-3
11 yrs							
M	87,8	75,3	7,9	80,9	71,9	3,1	−0,6
Me	87,5	76,9	5,8	81,3	73,8	3,	−0,5
SD	7,9	10,7	7,5	10,3	15,5	0,8	1,9
min-max	70–100	57,5–95	−3-24,6	62,5-97,5	32,5-97,5	1,96–5,5	−5-3
12 yrs							
M	89,3	75,2	8,7	80	73	3,6	−0,6
Me	90	72,5	9,3	80,8	75	3,5	−1
SD	6,7	9,5	4,7	13,5	9,3	1	1,2
min-max	75–100	62,5-97,5	−1,5-13,9	48–97,5	52,5–90	2,2-6,2	−3-2
13 yrs							
M	90,3	81,8	5,3	82,1	78,3	3,8	−0,3
Me	90	85	4,6	83,8	80	3,2	−1
SD	7,4	11,4	6,1	8	9,6	1,1	1,7
min-max	75–100	55–95	−5,6-22,8	67,5–95	55–95	2,2-6,5	−3-3
14 yrs							
M	89	80,1	5,7	83,9	75,4	3,2	−0,5
Me	91,3	82,5	4,7	85	75,6	3	−0,5
SD	7,9	12,3	7,4	12	14,8	0,8	1,6
min-max	75–100	47,5-97,5	−2,9-26,9	55–100	40–95	2–5,5	−4-2
15 yrs							
M	89,1	83,1	3,6	86,6	79,6	3,3	−0,7
Me	90	82,5	3,7	87,5	77,5	3,1	−1
SD	7,4	7,9	4,1	9,4	13,1	0,8	−1,4
min-max	75–100	67,5-97,5	−3-11,5	70–100	52–100	1,92–5	−3-3
Adults							

Table 2 (continued)

Age group	DDT (%)			DPT (%)	FPT (%)	GDT (ms)	aSpN (dB)
	R	L	REA				
M	91,7	85,7	3,4	88,3	82,6	3	−0,3
Me	91,5	85	2	90	82,5	3	−0,5
SD	5,1	5,7	3,2	8,2	7,1	0,7	1,9
min-max	83–100	76–100	0–12,3	70–100	71,5-97,5	1,9 −4,2	-4-3

DDT Dichotic Digit Test, *R* right, *L* left, *REA* right ear advantage, *DPT* Duration Pattern Test, *FPT* Frequency Pattern Test, *GDT* Gap Detection Test, *aSpN* adaptive Speech-in-Noise

showed significantly lowered scores than the adults but, with the Bonferrroni adjustment, only children at the of 9 showed a trend towards less correct responses in this test compared with the adult group (Table S2). All age categories showed the right ear advantage (REA) which was higher in the 7–8 age range than in both 15-year-olds and adults (Table S3). In the DPT the 7-year-olds performed more poorly than the 13-, 14-, 15-year-olds and the adults but there was also a trend towards lowered scored at the age of 7 compared with the age of 10–11 (Table S4). Relative to all age groups above 10, the FPT performance in both 7- and 8-year-olds were decreased, however, after the adjusting for multiple comparisons, only the differences between the age of 7 and the groups older than 12 as well as between the 8-year-olds and the age categories above 11 reached the significance level (Table S5). The percentage of correct responses in the DPT was significantly higher than in the FPT in all age groups except for 7-year olds whose performance was comparable in both these tests (Table 3). The test-retest reliability, assessed by calculating the intra-class correlation coefficients (ICC) based on two CAP evaluations in the 12-year-olds, could be considered as "good" for the DPT and DDT (left ear) and "moderate" for the DDT (right ear), FPT, GDT and aSpN (Table 4, Koo & Li, 2016).

Dichotic Listening Improves in Polish Children Aged 7–13 Years

In the present study the DDT outcomes for the right ear became adult-like already at the age of 10 (Fig. 1, Table S1) and even the 7-year-olds performed very well in this test (about 75% correctness level, Table 2). Therefore, a slight improvement across the age range considered, may reflect accidental fluctuations of attention/working memory rather than the CANS maturation process. The lack of significant differences in the right ear DDT outcomes between the age categories above 7 years were probably due to the ceiling effects.

The left ear DDT performance across 7–12 age range was still lower compared with the adults and the 13-year-olds achieved the adult-like scores (Fig. 1, Tables 2, S2). These findings indicate that the development of dichotic listening in Polish children is completed until 13 years of age. Basically, our outcomes are consistent with previous reports (Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002; Pedersen, Dahl-Hansen, Christensen-Dalsgaard, & Brandt, 2017; Stollman et al., 2004), however, most authors investigated the improvement in listening of dichotic digits in children younger than 12 years arguing that CAP continue to develop until this age and the results of older groups are relatively stable and comparable to those obtained by adults (Keith, 2000; Bellis, 2003; Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016, Schochat & Musiek, 2006). Our DDT results are comparable with those provided by Neijenhuis et al. (2002) in children (aged 7–12 years), adolescents (14–16 years) and adults (in both right and left ear the values in the latter two groups were almost the same but the 12-year-olds still performed worse compared to them). The course of the left ear dichotic listening development up to 13 may result from both continuous maturation process of the auditory cortex/corpus callosum (Moncrieff, 2011) and developmental improvement in non-auditory cognitive skills (Stavrinos et al., 2018; Tomlin, Dillon, Sharma, & Rance, 2015).

Despite that our DDT results in children aged 7–10 years (Table 2) were comparable with those previously reported in the Polish population (Włodarczyk et al., 2019), in contrast to this study we failed to demonstrate significantly lowered left ear scores in the 7–8-year-olds relative to the 9- and 10-year-olds as well as better right ear performance in 10-year-olds than at the age of 8 years. These discrepancies may result from different statistical methods used to analyze the data.

We observed the greatest improvement in the left ear DDT with age, i.e. from 60% to 69% of correct responses, between 8 and 9 years (Fig. 1, Table 2). A similar, 10%-difference between 8- and 9-year-olds, was also reported by other authors (Mattsson et al., 2018; Pedersen et al., 2017; Włodarczyk et al., 2019). The course of age-related improvement in the DDT may also reflect developmental changes in divided attention since the measures of both these functions found to be inter-correlated (Stavrinos et al., 2018). It is possible, then, that the DDT captures the moment of the highest

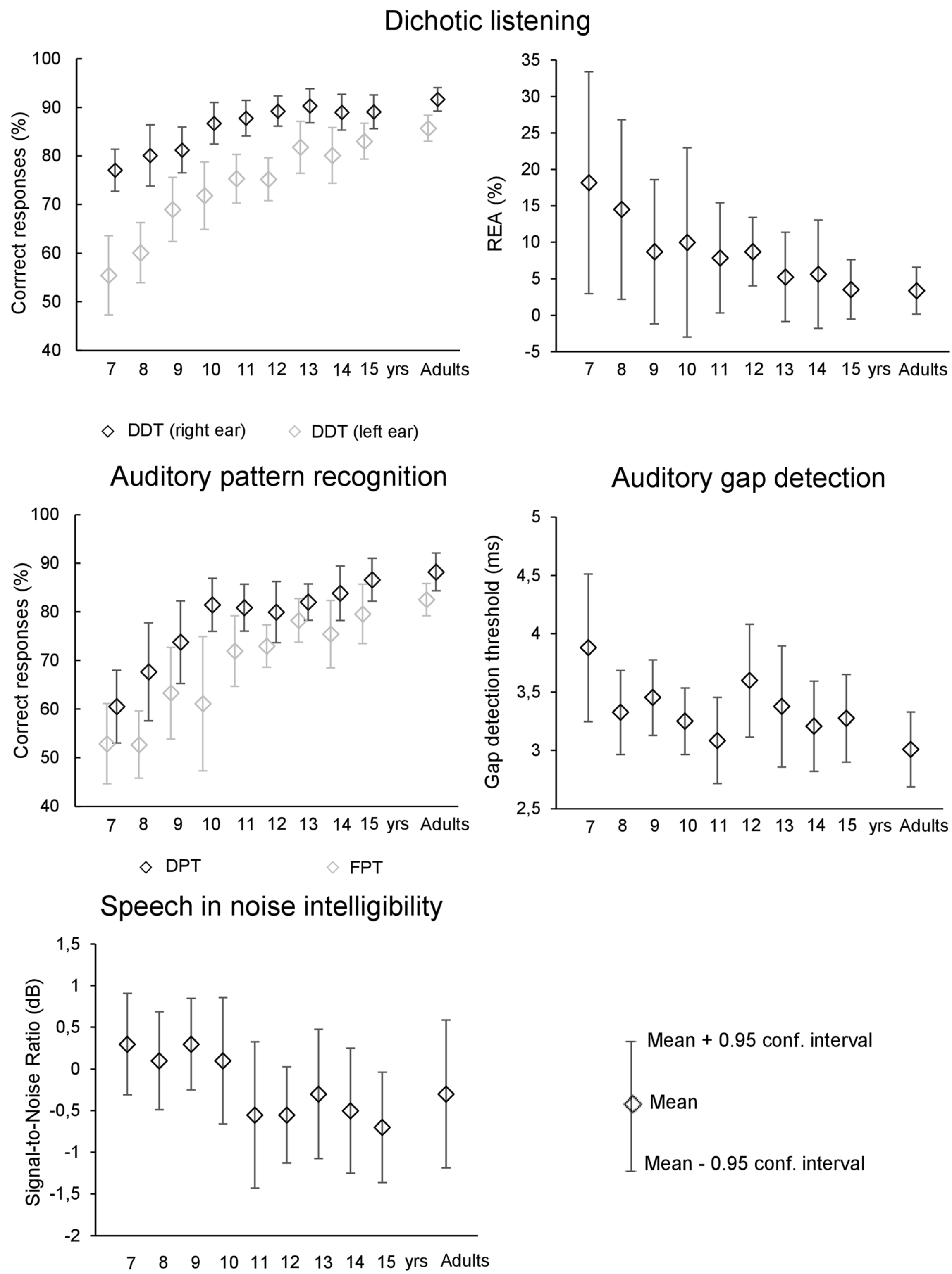

Fig. 1 Boxplots of the scores on the CAP tests among children and adolescents in the age range from 7 to 16 years of age. The centre line in each box indicates the mean value and the whiskers represent 0.95 confidence intervals. DDT – Dichotic Digit Test, DPT – Duration Pattern Test, FPT – Frequency Pattern Test

(in the age range considered) progress in attention and working memory development and/or the most intensive CANS maturation process. Any conclusions about that should be considered with caution since the great improvement in the

Table 3 Comparisons between the right and left ear DDT scores and between the DPT and FPT performance in particular age groups

Age categories	DDT right ear vs. left ear				DPT vs. FPT			
	95% CI		t value	*p* value	95% CI		t value	p value
	Low	High			Low	High		
7 years	14,98	28,03	6,28	< 0,01	0,03	16,97	1,81	0,123
8 years	11,84	26,75	5,49	< 0,01	6,87	23,39	3,72	< 0,01
9 years	6,43	18,18	4,04	< 0,01	2,84	18,33	2,77	0,01
10 years	6,57	23,28	3,57	< 0,01	9,04	31,55	3,45	< 0,01
11 years	7,56	17,36	4,85	< 0,01	4,79	13,4	4,09	< 0,01
12 years	10,65	17,03	8,45	< 0,01	2,6	11,3	3,06	< 0,01
13 years	4,85	12,72	4,03	< 0,01	1,1	6,56	2,83	0,01
14 years	4,5	13,75	3,72	< 0,01	2,98	14,33	2,76	0,01
15 years	3,24	9,26	3,92	< 0,01	3,28	11,28	3,58	< 0,01
Adults	3,44	8,6	4,74	< 0,01	1,46	9,86	2,87	0,02

DDT Dichotic Digit Test, *DPT* Duration Pattern Test, *FPT* Frequency Pattern Test, *CI* confidence interval

dichotic digits scores for the left ear between 8 and 9 years has been not demonstrated by all authors (e.g. Cameron et al., 2016; Kelly, 2007; McDermott et al., 2016).

Interestingly, the youngest age groups in our study (7- and 8-year-olds) appear to achieve less correct responses in the left ear DDT compared with their peers from other countries (Cameron et al., 2016; Kelly, 2007; McDermott et al., 2016; Pedersen et al., 2017). This observation could be explained by the fact that, unlike to the test versions used in the aforementioned studies, the digit sequences to repeat in the Polish task, were longer (not only mono- but also bi-syllabic words were included). Therefore, our task might have higher cognitive demands which could affect the results, especially in younger listeners. Perhaps it would be advisable to include to the Polish psychoacoustic battery the dichotic test containing other verbal material than numbers.

REA Effect

In our study the DDT scores in the right ear were significantly better than those obtained in the left ear in each age group including young adults (Table 3). The large REA for dichotic verbal material (e.g. digits) has been relatively well documented in normally developing children (e.g. Kelly, 2007; Kimura, 1961a, 1961b; Mattsson et al., 2018;McDermott et al., 2016 ; Weihing et al., 2015), especially in young listeners (Hugdahl et al., 1990; Kimura, 1961a, 1961b), and is considered as being indicative for the immaturity of CANS (less myelination) or greater suppression from the dominant ear (Moncrieff, 2011; Musiek & Weihing, 2011).

Considering the course of changes in the REA with age, the right ear dominance in our study was reduced from about 20% in the 7-year olds to about 5% and even less in the 13-year

Table 4 Test-retest reliability and learning effects for particular CAP tests

CAP tests	ICC					Test-retest difference (second – first)			
	Estimate	95% CI		Value	p	Mean	p value	95% CI	
		Low	High					Low	High
DDT R	0,74	0,34	0,9	3,82	< 0,01	0,75	0,64	−2,42	3,7
DDT L	0,75	0,38	0,9	4,04	< 0,01	−0,05	0,98	−3,75	3,42
DPT	0,8	0,5	0,9	5,05	< 0,01	3,9	0,15	−0,87	8,95
FPT	0,74	0,35	0,9	3,87	< 0,01	3,4	0,15	−1,07	7,55
GDT	0,6	−0,01	0,84	2,51	0,03	−0,54	0,02	−0,96	−0,17
aSpN	0,66	0,14	0,87	2,93	0,01	−0,25	0,457	−0,9	0,35

CAP Central Auditory Processes, *ICC* intra-class correlation coefficient, *CI* confidence interval, *SD* Standard Deviation, *DDT* Dichotic Digit Test, *R* right, *L* left, *REA* right ear advantage, *DPT* Duration Pattern Test, *FPT* Frequency Pattern Test, *GDT* Gap Detection Test, *aSpN* adaptive Speech-in-Noise olds and adults, respectively (Fig. 1, Table 2). Our data are comparable with those found in Norwegian children (Mattsson et al., 2018) who showed the REA decline from about 20% (7-year olds) to 6% in the 11–12-year-olds. In English-speaking children in USA (McDermott et al., 2016; Weihing et al., 2015) or New Zealand (Kelly, 2007) for whom a decrease of the REA from 3 to 10% in the 7–8 year-olds to the ceiling effect in children older than 11 was observed, the right ear dominance for the dichotic digits appears to be smaller than in Polish children in each age category between 7 and 12 years. Since the larger REA indexes have been reported for higher linguistic material (Hugdahl et al., 1990; Kimura, 1961a, 1961b) it is possible that digits in Polish language are more complex stimuli that those in English (in the Polish version of the test 6 of 10 digits are bi-syllabic words) and this may lead to higher REAs. Furthermore, in contrast to, e.g. Mattsson et al. (2018), where the handedness of participants was not controlled, in the current work only the results from right-handed persons were reported which may also partially explain the increased REA values in our study.

Duration and Frequency Pattern Recognition Improve at Different Rate in Children Aged 7–13 Years

Similar to most previous reports (Dekerle & Meunier, 2018; Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002; Schochat & Musiek, 2006; Stollman et al., 2004; Weihing et al., 2015) we found significant age effect in the auditory patterns performance (Fig. 1, Table S4-S5). Comparable with the previous studies (e.g. McDermott et al., 2016; Pedersen et al., 2017) in the youngest groups for both DPT and FPT scores there were large standard deviations which systematically decreased with age. Since the developmental variability of cortical responses is thought to be indicative for sustained attention (Strait, Slater, Abecassis, & Kraus, 2014) and, for example, FPT performance was thought to correlate with academic skills and real-life listening difficulty (Tomlin et al., 2015), the age-related improvement (both higher correctness level and lowered variability of the scores) in children in acoustic pattern recognition may just reflect development of general cognitive functions (attention, working memory). Furthermore, an ability to recognize the temporal patterns is needed to extract and use prosodic aspects of speech such as rhythm, stress and intonation (Fletcher, 2010). Therefore, the changes of the FPT and DPT performance, reported here, may also reflect an increase in linguistic area.

The DPT and FPT results in our study were comparable with those provided by Włodarczyk et al. (2019) and, as was the case with the DDT, unlike the results demonstrated in this paper, we did not find any significant differences between the 7-year-olds and 9–10-year-olds in the DPT (probably due to different statistical analysis). In the previous paper the age effect in the FPT was not explored because of a huge variability of the scores. In the present study we also showed large standard deviations in this test outcomes, especially in the youngest groups, however, these values were very similar to those found by other authors (Kelly, 2007; Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002) and not high enough to stop us from analyzing the developmental changes in frequency pattern recognition.

According to our expectations, the FPT turned out to be more challenging than the DPT for all age categories (see: Table 3 for the results of direct comparisons between DPT and FPT scores in each group) which is not quite consistent with the results of other studies (Mattsson et al., 2018; McDermott et al., 2016; Neijenhuis et al., 2002; Romero-Díaz et al., 2011; Stollman et al., 2004). The DPT scores improved the most in the 7–10 age range, from 60% to 81% (Table 2) whereas in the FPT performance increased from ca. 53% of correct responses in 7-year old to ca. 80% in the 11- and 12-year-olds (Fig. 1, Table 2). The greatest progress in the FPT was observed between 7 and 9 years of age (from 53% of correct responses to 63%) and also between the age of 10 and 11 (from the correctness level of 61% to ca. 72%). Since in our study in both these tests the progress between subsequent age categories was relatively small, the significant differences were found only between the 7-year-olds and the groups above 12 (DPT) and in case of the FPT between the age of 7–8 and the participants above 11–12. The DPT performance became adult-like much earlier than the FPT (at the age of 10 and 13, respectively).

The highest discrepancy between the duration and frequency pattern scores was found in the 10-year-olds, i.e. lower correctness level and increased variability of test results in the FPT (Fig. 1, Table 2). As we have mentioned in the Introduction section, in the present study Polish children, mostly the younger ones, definitely prefer to verbalize the tones differently, e.g. *thin* and *thick* despite that they were encouraged to respond using *high* and *low* labels. On the other hand, in the DPT there is only one way to report the order of the sounds, i.e. using *short* or *long* labels. Since psychological studies clearly demonstrate that metaphors in language can shape people's nonlinguistic space-pitch mental representations (Dolscheid, Shayan, Majid, & Casasanto, 2013) and around the age of 10 years children just start to understand and make sense of metaphors (Vosniadou, 1987) it is possible that lowered and more variable FPT performance reflect uneven development of an ability to comprehend and produce metaphorical language, observed especially at the beginning of this process. Therefore, the reason why Polish children performed better in the DPT than FPT might be a difficulty in understanding and verbalization of responses in the latter test.

Another possible explanation of this discrepancy is that a lower correctness level of the FPT in Polish children results from poorer music education (most public schools in Poland do not pay much attention to the child's musical skills development). This is even more likely when we consider that all participants who attended additional music classes were excluded from our study. The FPT results, comparable with ours, were found in Spanish-speaking children in Brazil (Schochat & Musiek, 2006) where there is no music education system. Thus, we cannot rule out a possibility that Polish-speaking children, adolescents and adults did not deal so well with the frequency patterns because of insufficient music training.

The observed differences between the duration and frequency pattern results could be also explained with a reference to a specificity of Polish language. One of distinctive features of Polish is a length of consonants which is crucial for intelligibility and expressiveness of the language (Nau et al., 2016). Since Polish children are trained in duration discrimination while listening to and using Polish every day, they might also achieve better scores in the DPT.

Children in our study were less correct in the FPT compared with their English-speaking peers who obtained ca. 65–70% of correct responses at the age of 7 years and ca. 88–91% when they were 11–12-year old (Bellis 2003; Kelly, 2007; McDermott et al., 2016; Weihing et al., 2015). However, in contrast to the aforementioned studies where 3-element auditory sequences were delivered monaurally (albeit there were no significant between-ear differences), we used bilateral tone triplets. Therefore, different stimulus presentation mode could partly account for the discrepancy in the scores achieved in this test by English- and Polish-speaking children. This effect may also arise from the differences in intonation between these languages: some structures of nuclear pitch patterns are present in English but absent in Polish, e.g., in contrast to English, in Polish "*low-high-low*" or "*high-low-high*" are not present (Demenko, 1999) and, therefore, the perception of auditory patterns composed of high and low tones might be not natural for Polish children.

Gaps- and Speech-in-Noise Detection Are Already Adult-like in 7-Year-Old Children

Gaps-in-noise detection is a commonly used procedure to investigate temporal resolution, relatively not much affected by attention or working memory of the listeners, and with proved clinical utility (Efron et al., 1985; Musiek et al., 2005). In the present study we used the GDT with an adaptive algorithm to determine gap detection thresholds. Therefore, prior to using this test at the clinic, it is highly recommended to determine how the results of this test change with age in normally developing children and adolescents, especially when it has been suggested that the threshold values may be affected by the stimulus parameters and procedure (Chermak & Lee, 2005; Phillips, Comeau, & Andrus, 2010). The GDT results in our study (Fig. 1, Table 3) were relatively stable with the age range considered and comparable with those of other authors (do Amaral et al., 2013; Bellis 2003; Irwin et al., 1985; Ismaail et al., 2019; Mattsson et al., 2018; Shinn et al., 2009). It suggests that the mechanism responsible for encoding temporal aspects of auditory information is well developed even in the youngest school-age children. In our study to correctly detect a gap embedded in white noise, the minimum gap length ranged from approximately 3,9 ms in 7-year-olds to about 3,8 ms in 13-year old and 3 ms in young adults was needed (Table 2) revealing a slight but inconsistent improvement in the GDT with age. In most studies in normal populations the auditory gap detection thresholds were about 3–4 ms (e.g. Irwin et al., 1985; Ismaail et al., 2019; Mattsson et al., 2018), with higher values being indicative for the temporal lobe lesions (Musiek et al., 2005) that are not supposed to be found in normally developing children.

Our procedure and way of calculating the results are the most similar to those of the test developed by Lister, Roberts, and Lister (2011), i.e. the Adaptive Tests of Temporal Resolution (ATTR), where the gap detection thresholds are determined with the use of an adaptive algorithm. Unlikely to our study, they found considerable improvement in this test within the age range from 7 to 12 years. The discrepancy of the results between the AATR and our test may arise from different procedures applied (in the ATTR the listeners were exposed to the pairs of noise bursts and had to decide which of them contained a larger gap whereas in the GDT we asked the listeners to attend a series of white noises and press the button when those with embedded gap occurred). Furthermore, our study differs from Lister et al. (2011) with respect to the properties of stimuli applied and the way of calculating the results. Other well-known tools are the Random Gap Detection Test (Keith, 2000) that actually measures the auditory fusion threshold (the averaged interval at which the tone pairs, separated by a silent gaps, are perceived as two with the interval at which the tone pairs are perceived as one) and the Gaps-in-Noise (GiN) (Musiek et al., 2005) which consists in counting and reporting orally the number of gaps heard in white-noise segments. Although both these tests are much different from the task in our study, the outcomes and dynamics of their improvement in children up to the age of 12 years are comparable to those that we observed. This is in accordance with the conclusion made by (Chermak & Lee, 2005) that different versions of gap detection test produce comparable results.

According to our prediction, both auditory gap detection and speech-in-noise tests scores remained unchangeable in the age range considered. Basically, our outcomes are congruent with other studies where discrimination abilities for speech sounds appeared to be developed at relatively young ages (up to about age of 8 years) and older children did not differ from young adults in this ability (e.g. Keith, 2000; Neijenhuis et al., 2002; Wilson et al., 2010). We found the largest, but not statistically significant, decline of the SNR value between 10-

and 11-year olds. We considered this effect as being caused by accidental fluctuations od attention rather than developmental changes of auditory brainstem where the ability to hear speech in the presence of background noise is represented (Song, Skoe, Banai, & Kraus, 2011).We did not expect that our, relatively easy, test with the single words exposed against background noise, would be sensitive enough to capture these subtle developmental changes. Furthermore, since there are no evidence on the relationship between speech-in-noise performance and cognitive abilities in typically developing children aged 5.5–13 years (von Koss Torkildsen, Hitchins, Myhrum, & Wie, 2019), a slight improvement in the aSpN in our study resulting from other reasons than the brainstem maturation process, may be also excluded.

In the present study an adaptive algorithm to determine the minimum SNR ratio, needed to repeat words correctly, was applied. In other versions of the task, words with the same SNR are exposed to a child and a target stimulus is of greater intensity than the background noise (Keith, 1995). In this case, the number of correct responses for particular SNR is calculated. In our opinion, however, determination of the minimum SNR value, using an adaptive measurement procedure, can provide more precise information about an individual's speech perception ability and be more useful at the clinic. Despite different versions of speech-in-noise test used worldwide, with different verbal material, consistently with most previous findings, we found no significant improvement of speech-in-noise intelligibility with age from 7 to 16 years. Therefore, the aSpN may be considered as a part of CAP evaluation.

Test-Retest Reliability

As it is shown in Table 4, ICCs for all CAP tests appear to be satisfactory. The lowest values were found for the adaptive procedures, the GDT and aSpN. Furthermore, only in the gap detection task there was a considerable learning effect. These results may suggest that the adaptive algorithms, used in the GDT and aSpN to determine the threshold values, should be modified to provide more consistent scores. However, since re-testing was performed for only one age group (12-year-olds) we refrain from any general conclusions about that.

Limitations and Further Directions

We are aware of the fact that age groups studied here could be bigger to ensure greater reliability of the reported effects. While interpreting the outcomes one should take into account that due to higher variability of the test outcomes in younger than older participants, some differences between the age groups (as small as in our study), may not reach the significance level. Evaluation of the same subjects at particular age moments (e.g. every year from 7 to adulthood), similarly as Stollman et al. (2004) did, might provide more throughout insight into a course of CAP performance improvement with age. Furthermore, all tests, applied in the present study, have already been recommended as possible screening for CAPD (Iliadou et al., 2017; Jerger & Musiek, 2000) in clinical practice. To make them useful at the clinic in Poland it would be advisable to determine the age-appropriate normative data representative for Polish-speaking population. It would be also desired to take into account how cognitive development of the child (e.g. attention and language) affects the improvement of particular CAP performance with age in children and adolescents.

Conclusions

Our study demonstrated the improvement in dichotic listening and recognition of frequency and duration patterns across the age range from 7 to 13 years. The DPT performance was adult-like much earlier (in 10-year-olds already) than the DDT and FPT outcomes where the adult levels were not achieved until the age of 13. The gap detection and speech-in-noise intelligibility were adult-like and relatively stable between 7 and 16 years. Thus, particular auditory processes evolve at different rates, consistently with previous findings.

In comparisons with other studies, the development of dichotic listening and the ability to recognize frequency patterns appears to be slightly delayed in Polish children. The course of age - related improvement in the tests measuring these auditory processes may be depended on the linguistic/cultural background of the person being examined and the rate of development of his/her non-auditory cognitive abilities (attention, language). Since the linguistically-loaded psychoacoustic tests (dichotic listening, speech-in-noise comprehension) do not measure "pure" central auditory processes, their results should be interpreted with caution. It is recommended to consider using more accurate measures of auditory processing even in case of dealing with nonverbal sounds. Unification of the response method (e.g. *humming*) would allow to compare the frequency pattern performance between Polish and non-Polish speaking children.

Unlike to some populations, the frequency patterns were more difficult to recognize for Polish children and adolescents than the sequences of sounds differing in duration. This effect may be explained in terms of a specificity of Polish language (the lack of nuclear accent types that are present, e.g. in English), insufficient musical education or quite misleading form of response format in the FPT (the labels for low and high tones, required in this test, do not come naturally to the Polish children).

Our study also provided the reference values for the psychoacoustic tests in both children and adolescents, aged from

7 to 16 years, complementing those previously found for Polish children up to 10 years of age (Włodarczyk et al., 2019). We also added to the Polish psychoacoustic battery two tasks measuring important aspects of auditory processing, i.e. temporal resolution and speech-in-noise intelligibility. Since all the tests achieved satisfactory reliability, they could be recommended to use for CAPD screening.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12144-021-01540-x.

Acknowledgements This study was partially supported by the grant of the Polish National Science Centre no. UMO-2013/08/W/HS6/00333, entitled: *"NeuroPerKog: development of phonematic hearing and working memory in infants and children".*

Authors' Contributions M.L. designed the study, analyzed the data and wrote the manuscript in consultation with R.M.

M.G. J.D. and E.W. collected the data and helped shape the manuscript.

H.S. supervised the study.

Data Availability The data being reported here are available from the corresponding author on reasonable request.

Code Availability Not applicable.

Declarations

Conflicts of Interest/Competing Interests On behalf of all authors, the corresponding author states that there is no conflict of interest. The authors alone are responsible for the content and writing of the paper.

References

Association (ASHA), A. S.-L.-H. (2005). (Central) auditory processing disorders. *American Speech-Language-Hearing Association*. https://doi.org/10.1044/policy.TR2005-00043.

Association (BSA) (2018). Position statement and practice guidance. Auditory Processing Disorder (APD). https://www.thebsa.org.uk/wp-content/uploads/2018/02/Position-Statement-and-Practice-Guidance-APD-2018.pdf.

Bamiou, D.-E. (2001). Aetiology and clinical presentations of auditory processing disorders—a review. *Archives of Disease in Childhood, 85*(5), 361–365. https://doi.org/10.1136/adc.85.5.361.

Bao, Y., Szymaszek, A., Wang, X., Oron, A., Pöppel, E., & Szelag, E. (2013). Temporal order perception of auditory stimuli is selectively modified by tonal and non-tonal language environments. *Cognition, 129*(3), 579–585. https://doi.org/10.1016/j.cognition.2013.08.019.

Bellis, T. J. (2003). *Assessment and management of central auditory processing disorders in the educational setting: From science to practice* (2nd ed.). Clifton Park, NY: Thomson Learning.

Buss, E., Porter, H. L., Hall, J. W., & Grose, J. H. (2017). Gap detection in school-age children and adults: Center frequency and ramp duration. *Journal of Speech, Language, and Hearing Research, 60*(1), 172–181. https://doi.org/10.1044/2016_JSLHR-H-16-0010.

Cameron, S., & Dillon, H. (2008). The Listening in spatialized noise–sentences test (LISN-S): comparison to the prototype LISN and results from children with either a suspected (Central) auditory processing disorder or a confirmed language disorder. *Journal of the American Academy Audiology, 19*, 377–391.

Cameron, S., Dillon, H., & Newall, P. (2006). The Listening in Spatialized Noise test: Normative data for children: La prueba de audición en ruido espacializado: datos normativos para niños. *International Journal of Audiology, 45*(2), 99–108. https://doi.org/10.1080/14992020500377931.

Cameron, S., Glyde, H., Dillon, H., Whitfield, J., & Seymour, J. (2016). The dichotic digits difference test (DDdT): Development, normative data, and test-retest reliability studies part 1. *Journal of the American Academy of Audiology, 27*(6), 458–469. https://doi.org/10.3766/jaaa.15084.

Chermak, G. D., & Lee, J. (2005). Comparison of Children's performance on four tests of temporal resolution. *Journal of the American Academy of Audiology, 16*(8), 554–563. https://doi.org/10.3766/jaaa.16.8.4.

Chermak, G. D., & Musiek, F. E. (1997). *Central auditory processing disorders: New perspectives*. San Diego, CA: Singular Publishing Group.

Cooke, M. (2006). A glimpsing model of speech perception in noise. *The Journal of the Acoustical Society of America, 119*(3), 1562–1573. https://doi.org/10.1121/1.2166600.

Cowan, N. (2016). Working memory maturation: Can we get at the essence of cognitive growth? *Perspectives on Psychological Science, 11*(2), 239–264. https://doi.org/10.1177/1745691615621279.

Dawes, P., & Bishop, D. V. M. (2010). Psychometric profile of children with auditory processing disorder and children with dyslexia. *Archives of Disease in Childhood, 95*(6), 432–436. https://doi.org/10.1136/adc.2009.170118.

Dawes, P., & Bishop, D. V. M. (2007). The SCAN-C in testing for auditory processing disorder in a sample of British children. *International Journal of Audiology, 46*(12), 780–786. https://doi.org/10.1080/14992020701545906.

DeBonis, D. A. (2015). It is time to rethink central auditory processing disorder protocols for school-aged children. *American Journal of Audiology, 24*(2), 124–136. https://doi.org/10.1044/2015_AJA-14-0037.

Dekerle, M., & Meunier, F. (2018). Central auditory processing development in primary school children, *2018*(01), 14.

Demenko, G. (1999). *Analiza cech suprasegmentalnych języka polskiego na potrzeby technologii mowy (Wyd. 1.). Analysis of suprasegmental features of the Polish language for the speech technology* (I ed.). Poznań: Adam Mickiewicz University Press.

do Amaral, M. I. R., Martins, P. M. F., & Colella-Santos, M. F. (2013). Temporal resolution: assessment procedures and parameters for school-aged children. *Brazilian Journal of Otorhinolaryngology, 79*(3), 317–324. https://doi.org/10.5935/1808-8694.20130057.

Dolscheid, S., Shayan, S., Majid, A., & Casasanto, D. (2013). The thickness of musical pitch: Psychophysical evidence for linguistic relativity. *Psychological Science, 24*(5), 613–621. https://doi.org/10.1177/0956797612457374.

Efron, R., Yund, E. W., Nichols, D., Efron, R., Yund, E. W., Nichols, D., & Crandall, P. H. (1985). An ear asymmetry for gap detection following anterior temporal lobectomy. *Neuropsychologia, 23*(1), 43–50. https://doi.org/10.1016/0028-3932(85)90042-9.

Eggermont, J. J., & Ponton, C. W. (2003). Auditory-evoked potential studies of cortical maturation in Normal hearing and implanted children: Correlations with changes in structure and speech perception. *Acta Oto-Laryngologica, 123*(2), 249–252. https://doi.org/10.1080/0036554021000028098.

Eggermont, J. J., Ponton, C. W., Coupland, S. G., & Winkelaar, R. (1991). Frequency dependent maturation of the cochlea and brainstem evoked potentials. *Acta Oto-Laryngologica, 111*(2), 220–224. https://doi.org/10.3109/00016489109137378.

Fitzroy, A.B., Krizman, J., Tierney, A., Agouridou, M., Kraus, N. (2015). Longitudinal maturation of auditory cortical function during adolescence. *Frontiers in Human Neuroscience,* 9, 530. https://doi.org/10.3389/fnhum.2015.00530.

Fletcher, J. (2010). The prosody of speech: Timing and rhythm. In W. J. Hardcastle, J. Laver, & F. E. Gibbon (Eds.), *The Handbook of Phonetic Sciences* (1st ed., pp. 521–602). Hoboken: Wiley. https://doi.org/10.1002/9781444317251.ch15.

Fuente, A., & McPherson, B. (2006). Auditory processing tests for Spanish-speaking adults: An initial study: Pruebas de percepción auditiva para adultos hablantes del español: un estudio inicial. *International Journal of Audiology, 45*(11), 645–659.

Gomes, H., Molholm, S., Christodoulou, C., Ritter, W., & Cowan, N. (2000). The development of auditory attention in children. *Frontiers in Bioscience: a Journal and Virtual Library, 5*, D108–D120. https://doi.org/10.2741/gomes.

Harris, R. W., Nielson, W. S., McPherson, D. L., Skarzynski, H., & Eggett, D. L. (2004). Psychometrically equivalent polish bisyllabic words spoken by male and female talkers. *Audiofonologia, 25*, 1–15.

Hugdahl, K., Andersson, L., AsbjØrnsen, A., & Dalen, K. (1990). Dichotic listening, forced attention, and brain asymmetry in righ thanded and left handed children. *Journal of Clinical and Experimental Neuropsychology, 12*(4), 539–548. https://doi.org/10.1080/01688639008401000.

Iliadou, V. V., Ptok, M., Grech, H., Pedersen, E. R., Brechmann, A., Deggouj, N., et al. (2017). A European perspective on auditory processing disorder-current knowledge and future research focus. *Frontiers in Neurology, 8*, 622. https://doi.org/10.3389/fneur.2017.00622.

Irwin, R. J., Ball, A. K. R., Kay, N., Stillman, J. A., & Rosser, J. (1985). The development of auditory temporal acuity in children. *Child Development, 56*(3), 614–620. https://doi.org/10.2307/1129751.

Ismaail, N. M., Shalaby, A. A., & Ibraheem, O. A. (2019). Effect of age on gaps-in-noise test in pediatric population. *International Journal of Pediatric Otorhinolaryngology*, S0165587619301727. https://doi.org/10.1016/j.ijporl.2019.04.010.

Jerger, J., & Musiek, F. (2000). Report of the consensus conference on the diagnosis of auditory processing. *Journal of the American Academy of Audiology, 11*(9), 467–474.

Johnson, K. L., Nicol, T., Zecker, S. G., & Kraus, N. (2008). Developmental plasticity in the human auditory brainstem. *Journal of Neuroscience, 28*(15), 4000–4007. https://doi.org/10.1523/JNEUROSCI.0012-08.2008.

Karns, C. M., Isbell, E., Giuliano, R. J., & Neville, H. J. (2015). Auditory attention in childhood and adolescence: An event-related potential study of spatial selective attention to one of two simultaneous stories. *Developmental Cognitive Neuroscience, 13*, 53–67. https://doi.org/10.1016/j.dcn.2015.03.001.

Keith, R. W. (1995). Development and standardization of SCAN-A: Test of auditory processing disorders in adolescents and adults. *Journal of the American Academy of Audiology, 6*(4), 286–292.

Keith, R. W. (2000). Development and standardization of SCAN-C test for auditory processing disorders in children. *Journal of the American Academy of Audiology, 11*(8), 8.

Kelly, A. (2007). Normative data for Behavioural tests of auditory processing for New Zealand school children aged 7 to 12 years. *Australian and New Zealand Journal of Audiology, 29*(1), 60–64. https://doi.org/10.1375/audi.29.1.60.

Kimura, D. (1961a). Cerebral dominance and the perception of verbal stimuli. *Canadian Journal of Psychology/Revue canadienne de psychologie, 15*(3), 166–171. https://doi.org/10.1037/h0083219.

Kimura, D. (1961b). Some effects of temporal-lobe damage on auditory perception. *Canadian Journal of Psychology, 15*, 156–165.

Kimura, D. (1967). Functional asymmetry of the brain in dichotic listening. *Cortex, 3*(2), 163–178. https://doi.org/10.1016/S0010-9452(67)80010-8.

King, W. M., Lombardino, L. J., Crandell, C. C., & Leonard, C. M. (2003). Comorbid Auditory Processing Disorder in Developmental Dyslexia. *Ear and Hearing, 24*(5), 448–456. https://doi.org/10.1097/01.AUD.0000090437.10978.1A.

Koo, T. K., & Li, M. Y. (2016). A guideline of selecting and reporting Intraclass correlation coefficients for reliability research. *Journal of Chiropractic Medicine, 15*(2), 155–163. https://doi.org/10.1016/j.jcm.2016.02.012.

Krizman, J., Tierney, A., Fitzroy, A. B., Skoe, E., Amar, J., & Kraus, N. (2015). Continued maturation of auditory brainstem function during adolescence: A longitudinal approach. *Clinical Neurophysiology, 126*(12), 2348–2355. https://doi.org/10.1016/j.clinph.2015.01.026.

Leek, M. R. (2001). Adaptive procedures in psychophysical research. *Perception & Psychophysics, 63*(8), 1279–1292.

Lister, J. J., Roberts, R. A., & Lister, F. L. (2011). An adaptive clinical test of temporal resolution: Age effects. *International Journal of Audiology, 50*(6), 367–74. https://doi.org/10.3109/14992027.2010.551218.

Loo, J. H. Y., Bamiou, D.-E., & Rosen, S. (2013). The impacts of language background and language-related disorders in auditory processing assessment. *Journal of Speech, Language, and Hearing Research, 56*(1), 1–12. https://doi.org/10.1044/1092-4388(2012/11-0068).

Luders, E., Thompson, P. M., & Toga, A. W. (2010). The development of the Corpus callosum in the healthy human brain. *Journal of Neuroscience, 30*(33), 10985–10990. https://doi.org/10.1523/JNEUROSCI.5122-09.2010.

Ludwig, A. A., Fuchs, M., Kruse, E., Uhlig, B., Kotz, S. A., & Rübsamen, R. (2014). Auditory Processing Disorders with and without Central Auditory Discrimination Deficits. *Journal of the Association for Research in Otolaryngology: JARO. 15*(3): 441–64. https://doi.org/10.1007/s10162-014-0450-3.

Lutman, M. E. (1991). Degradations in frequency and temporal resolution with age and their impact on speech identification. *Acta Oto-Laryngologica, 111*(sup476), 120–126. https://doi.org/10.3109/00016489109127265.

Marriage, J., King, J., Briggs, J., & Lutman, M. E. (2001). The reliability of the SCAN test: Results from a primary school population in the UK. *British Journal of Audiology, 35*(3), 199–208. https://doi.org/10.1080/00305364.2001.11745237.

Mattsson, T. S., Follestad, T., Andersson, S., Lind, O., Øygarden, J., & Nordgård, S. (2018). Normative data for diagnosing auditory processing disorder in Norwegian children aged 7–12 years. *International Journal of Audiology, 57*(1), 10–20. https://doi.org/10.1080/14992027.2017.1366670.

McDermott, E. E., Smart, J. L., Boiano, J. A., Bragg, L. E., Colon, T. N., Hanson, E. M., et al. (2016). Assessing auditory processing abilities in typically developing school-aged children. *Journal of the American Academy of Audiology, 27*(2), 13.

McGraw, K. O., & Wong, S. P. (1996). Forming inferences about some intraclass correlation coefficients. *Psychological Methods, 1*(1), 30–46. https://doi.org/10.1037/1082-989X.1.1.30.

Moav, R., Nevo, N., & Banai, K. (2009). Central auditory processing development in adolescents with and without learning disabilities. *Journal of Basic and Clinical Physiology and Pharmacology, 20*(3), 207–217. https://doi.org/10.1515/JBCPP.2009.20.3.207.

Moncrieff, D. W. (2011). Dichotic listening in children: Age-related changes in direction and magnitude of ear advantage. *Brain and Cognition, 76*(2), 316–322. https://doi.org/10.1016/j.bandc.2011.03.013.

Moore, D. R., Cowan, J. A., Riley, A., Edmondson-Jones, A. M., & Ferguson, M. A. (2011). Development of Auditory Processing in 6- to 11-Yr-Old Children. *Ear and Hearing, 32*(3), 269–285. https://doi.org/10.1097/AUD.0b013e318201c468.

Mukari, S. Z., Keith, R. W., Tharpe, A. M., & Johnson, C. D. (2006). Development and standardization of single and double dichotic digit tests in the Malay language: Desarrollo y estandarización de pruebas de dígitos dicóticos sencillos y dobles en Lengua malaya. *International Journal of Audiology, 45*(6), 344–352. https://doi.org/10.1080/14992020600582174.

Murphy, C. F. B., Zachi, E. C., Roque, D. T., Ventura, D. S. F., & Schochat, E. (2014). Influence of memory, attention, IQ and age on auditory temporal processing tests: Preliminary study. *CoDAS, 26*(2), 105–111. https://doi.org/10.1590/2317-1782/2014494IN.

Musiek, F. E. (1983). Assessment of central auditory dysfunction: The dichotic digit test revisited. *Ear and Hearing, 4*(2), 79–83.

Musiek, F. E., Baran, J. A., & Pinheiro, M. L. (1990). Duration pattern recognition in normal subjects and patients with cerebral and cochlear lesions. *Audiology: Official Organ of the International Society of Audiology, 29*(6), 304–313.

Musiek, F. E. (1994). Frequency (pitch) and duration pattern tests. *Journal of the American Academy of Audiology, 5*(4), 4.

Musiek, Frank E, Baran, J. A., Bellis, T. J., & Chermak, G. D. (2010). Guidelines for the diagnosis, Treatment and Management of Children and Adults with Central Auditory Processing Disorder, 51.

Musiek, Frank E., & Chermak, G. D. (2015). Psychophysical and behavioral peripheral and central auditory tests. In *Handbook of Clinical Neurology* (Vol. 129, pp. 313–332). Elsevier. https://doi.org/10.1016/B978-0-444-62630-1.00018-4, 2015.

Musiek, F. E., Shinn, J. B., Jirsa, R., Bamiou, D.-E., Baran, J. A., & Zaida, E. (2005). GIN (gaps-in-noise) Test Performance in Subjects with Confirmed Central Auditory Nervous System Involvement. *Ear and Hearing, 26*(6), 608–618. https://doi.org/10.1097/01.aud.0000188069.80699.41.

Musiek, F. E., & Weihing, J. (2011). Perspectives on dichotic listening and the corpus callosum. *Brain and Cognition, 76*(2), 225–232. https://doi.org/10.1016/j.bandc.2011.03.011.

Nau, N., Hornsby, M., Karpiński, M., Klessa, K., Wicherkiewicz, T., & Wójtowicz, R. (2016). *Języki w niebezpieczeństwie: księga wiedzy. (Languages in danger: the book of knowledge).* Poznan: AMUR - Adam Mickiewicz University Repository, https://doi.org/10.14746/9788394719845.

Neijenhuis, K., Snik, A., Priester, G., van Kordenoordt, S., & van den Broek, P. (2002). Age effects and normative data on a Dutch test battery for auditory processing disorders: Efectos de la edad y datos normativos de una bateria de pruebas holandesa Para evaluar problemas de procesamiento auditivo. *International Journal of Audiology, 41*(6), 334–346. https://doi.org/10.3109/14992020209090408.

O'Connor, K. (2012). Auditory processing in autism spectrum disorder: A review. *Neuroscience & Biobehavioral Reviews, 36*(2), 836–854. https://doi.org/10.1016/j.neubiorev.2011.11.008.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9*(1), 97–113.

Paus, T., Zijdenbos, A., Worsley, K., Collins, D. L., Blumenthal, J., Giedd, J. N., Rapoport, J. L., Evans, A. C. (1999). Structural Maturation of Neural Pathways in Children and Adolescents: In Vivo Study. *Science*, 283(5409), 1908-11. https://doi.org/10.1126/science.283.5409.1908.

Pedersen, E. R., Dahl-Hansen, B., Christensen-Dalsgaard, J., & Brandt, C. (2017). Implementation and evaluation of a Danish test battery for auditory processing disorder in children. *International Journal of Audiology, 56*(8), 538–549. https://doi.org/10.1080/14992027.2017.1309467.

Phillips, D. P., Comeau, M., & Andrus, J. N. (2010). Auditory temporal gap detection in children with and without auditory processing disorder. *Journal of the American Academy of Audiology, 21*(6), 404–408. https://doi.org/10.3766/jaaa.21.6.5.

Picton, T. W., Alain, C., Woods, D. L., John, M. S., Scherg, M., Valdes-Sosa, P., Bosch-Bayard, J., & Trujillo, N. J. (1999). Intracerebral sources of human auditory-evoked potentials. *Audiology and Neuro-Otology, 4*(2), 64–79. https://doi.org/10.1159/000013823.

Pinheiro, M. L., & Ptacek, P. H. (1971). Reversals in the perception of noise and tone patterns. *The Journal of the Acoustical Society of America, 49*, 1778–1782.

Ponton, C., Eggermont, J. J., Khosla, D., Kwong, B., & Don, M. (2002). Maturation of human central auditory system activity: Separating auditory evoked potentials by dipole source modeling. *Clinical Neurophysiology, 113*(3), 407–420. https://doi.org/10.1016/S1388-2457(01)00733-7.

Ponton, C. W., Eggermont, J. J., Coupland, S. G., & Winkelaar, R. (1992). Frequency-specific maturation of the eighth nerve and brain-stem auditory pathway: Evidence from derived auditory brain-stem responses (ABRs). *The Journal of the Acoustical Society of America, 91*(3), 1576–1586. https://doi.org/10.1121/1.402439.

Ponton, C. W., Eggermont, J. J., Kwong, B., & Don, M. (2000). Maturation of human central auditory system activity: Evidence from multi-channel evoked potentials. *Clinical Neurophysiology, 111*(2), 220–236. https://doi.org/10.1016/S1388-2457(99)00236-9.

Ponton, C. W., Don, M., Eggermont, J. J., Waring, M. D., & Masuda, A. (1996). Maturation of human cortical auditory function: Differences between normal-hearing children and children with cochlear implants. *Ear and Hearing, 17*(5), 430–437. https://doi.org/10.1097/00003446-199610000-00009.

Pujol, J., Vendrell, P., Junqué, C., Martí-Vilalta, J. L., & Capdevila, A. (1993). When does human brain development end? Evidence of corpus callosum growth up to adulthood: Corpus callosum growth. *Annals of Neurology, 34*(1), 71–75. https://doi.org/10.1002/ana.410340113.

R Core Team (2020) R: A language and environment for statistical computing [internet]. Vienna, Austria: R Foundation for Statistical Computing. Available: https://www.R-project.org.

Riccio, C. A., Cohen, M. J., Garrison, T., & Smith, B. (2005). Auditory processing measures: Correlation with neuropsychological measures of attention, memory, and behavior. *Child Neuropsychology, 11*(4), 363–372. https://doi.org/10.1080/09297040490916956.

Riccio, C. A., Hynd, G. W., Cohen, M. J., Hall, J., & Molt, L. (1994). Comorbidity of central auditory processing disorder and attention-deficit hyperactivity disorder. *Journal of the American Academy of Child & Adolescent Psychiatry, 33*(6), 849–857. https://doi.org/10.1097/00004583-199407000-00011.

Romero-Díaz, A., Peñaloza-López, Y., García-Pedroza, F., Pérez, S. J., & Castro Camacho, W. (2011). Central auditory processes evaluated with psychoacoustic tests in Normal children. *Acta Otorrinolaringologica (English Edition), 62*(6), 418–424. https://doi.org/10.1016/j.otoeng.2011.06.003.

Rosenberg, G. G. (2011). Development of local child norms for the dichotic digits test, *Journal of Educational Audiology, 17*, 6–10.

Scharlock, D. P., Neff, W. D., & Strominger, N. L. (1965). Discrimination of tone duration after bilateral ablation of cortical auditory areas. *Journal of Neurophysiology, 28*(4), 673–681. https://doi.org/10.1152/jn.1965.28.4.673.

Schochat, E., & Musiek, F. E. (2006). Maturation of outcomes of behavioral and electrophysiologic tests of central auditory function. *Journal of Communication Disorders, 39*(1), 78–92. https://doi.org/10.1016/j.jcomdis.2005.10.001.

Sharma, A., Kraus, N., McGee, T. J., & Nicol, T. G. (1997). Developmental changes in P1 and N1 central auditory responses elicited by consonant-vowel syllables. *Electroencephalography and Clinical Neurophysiology/Evoked Potentials Section, 104*(6), 540–545. https://doi.org/10.1016/S0168-5597(97)00050-6.

Sharma, M., Purdy, S. C., & Kelly, A. S. (2009). Comorbidity of auditory processing, language, and Reading disorders. *Journal of Speech, Language, and Hearing Research, 52*(3), 706–722. https://doi.org/10.1044/1092-4388(2008/07-0226).

Shinn, J. B., Chermak, G. D., & Musiek, F. E. (2009). GIN (gaps-in-noise) performance in the pediatric population. *Journal of the American Academy of Audiology, 20*(4), 229–238. https://doi.org/10.3766/jaaa.20.4.3.

Skoe, E., Krizman, J., Anderson, S., & Kraus, N. (2015). Stability and plasticity of auditory brainstem function across the lifespan. *Cerebral Cortex, 25*(6), 1415–1426. https://doi.org/10.1093/cercor/bht311.

Song, J. H., Skoe, E., Banai, K., & Kraus, N. (2011). Perception of speech in noise: Neural correlates. *Journal of Cognitive Neuroscience, 23*(9), 2268–2279. https://doi.org/10.1162/jocn.2010.21556.

Stavrinos, G., Iliadou, V.-M., Edwards, L., Sirimanna, T., & Bamiou, D.-E. (2018). The relationship between types of attention and auditory processing skills: Reconsidering auditory processing disorder diagnosis. *Frontiers in Psychology, 9*, 34. https://doi.org/10.3389/fpsyg.2018.00034.

Stollman, M. H. P., van Velzen, E. C. W., Simkens, H. M. F., Snik, A. F. M., & van den Broek, P. (2004). Development of auditory processing in 6–12-year-old children: a longitudinal study: Desarrollo del procesamiento auditivo en niños de 6–12 años: un estudio longitudinal. *International Journal of Audiology, 43*(1), 34–44. https://doi.org/10.1080/14992020400050006.

Strait, D. L., Slater, J., Abecassis, V., & Kraus, N. (2014). Cortical response variability as a developmental index of selective auditory attention. *Developmental Science, 17*(2), 175–186. https://doi.org/10.1111/desc.12107.

Stuart, A., Givens, G.D., Walker, L.J., & Elangovan, S. (2006) Auditory temporal resolution in normal-hearing preschool children revealed by word recognition in continuous and interrupted noise. *The Journal of the Acoustical Society of America 119*(4), 1946–1949.https://doi.org/10.1121/1.2178700.

Sussman, E., Steinschneider, M., Gumenyuk, V., Grushko, J., & Lawson, K. (2008). The maturation of human evoked brain potentials to sounds presented at different stimulus rates. *Hearing Research, 236*(1–2), 61–79. https://doi.org/10.1016/j.heares.2007.12.001.

Sussman, E., Wong, R., Horváth, J., Winkler, I., & Wang, W. (2007). The development of the perceptual organization of sound by frequency separation in 5–11-year-old children. *Hearing Research, 225*(1–2), 117–127. https://doi.org/10.1016/j.heares.2006.12.013.

Tomlin, D., Dillon, H., Sharma, M., & Rance, G. (2015). The impact of auditory processing and cognitive abilities in children. *Ear and Hearing, 36*(5), 527–542. https://doi.org/10.1097/AUD.0000000000000172.

von Koss Torkildsen, J., Hitchins, A., Myhrum, M., & Wie, O. B. (2019). Speech-in-noise perception in children with Cochlear implants, hearing aids, developmental language disorder and typical development: The effects of linguistic and cognitive abilities. *Frontiers in Psychology, 10*, 2530. https://doi.org/10.3389/fpsyg.2019.02530.

Vandewalle, E., Boets, B., Ghesquière, P., & Zink, I. (2012). Auditory processing and speech perception in children with specific language impairment: Relations with oral language and literacy skills. *Research in Developmental Disabilities, 33*(2), 635–644. https://doi.org/10.1016/j.ridd.2011.11.005.

Vosniadou, S. (1987). Children and metaphors. *Child Development, 58*(3), 870. https://doi.org/10.2307/1130223.

Weihing, J., Guenette, L., Chermak, G., Brown, M., Ceruti, J., Fitzgerald, K., Geissler, K., Gonzalez, J., Brenneman, L., & Musiek, F. (2015). Characteristics of pediatric performance on a test battery commonly used in the diagnosis of central auditory processing disorder. *Journal of the American Academy of Audiology, 26*(7), 652–669. https://doi.org/10.3766/jaaa.14108.

Weiss, D., & Dempsey, J. J. (2008). Performance of bilingual speakers on the English and Spanish versions of the hearing in noise test (HINT). *Journal of the American Academy of Audiology, 19*(01), 005–017. https://doi.org/10.3766/jaaa.19.1.2.

Westerhausen, R., Luders, E., Specht, K., Ofte, S. H., Toga, A. W., Thompson, P. M., Helland, T., & Hugdahl, K. (2011). Structural and functional reorganization of the Corpus callosum between the age of 6 and 8 years. *Cerebral Cortex, 21*(5), 1012–1017. https://doi.org/10.1093/cercor/bhq165.

Wilson, R. H., & Burks, C. A. (2005). Use of 35 words for evaluation of hearing loss in signal-to-babble ratio: A clinic protocol. *Journal of Rehabilitation Research and Development, 42*(6), 839–852.

Wilson, R. H., Farmer, N. M., Gandhi, A., Shelburne, E., & Weaver, J. (2010). Normative data for the words-in-noise test for 6- to 12-year-old children. *Journal of Speech, Language, and Hearing Research, 53*(5), 1111–1121. https://doi.org/10.1044/1092-4388(2010/09-0270).

Włodarczyk, E. A., Szkiełkowska, A., Skarżyński, H., Miaśkiewicz, B., & Skarżyński, P. H. (2019). Reference values for psychoacoustic tests on polish school children 7–10 years old. *PLoS One, 14*(8), e0221689. https://doi.org/10.1371/journal.pone.0221689.

Woods, A. G., Peña, E. D., & Martin, F. N. (2004). Exploring possible sociocultural Bias on the SCAN-C. *American Journal of Audiology, 13*(2), 173–184. https://doi.org/10.1044/1059-0889(2004/022).

Yathiraj, A., & Vanaja, C. S. (2015). Age related changes in auditory processes in children aged 6 to 10 years. *International Journal of Pediatric Otorhinolaryngology, 79*(8), 1224–1234. https://doi.org/10.1016/j.ijporl.2015.05.018.

Zaidan, E., & Baran, J. A. (2013). Gaps-in-noise (GIN ©) test results in children with and without reading disabilities and phonological processing deficits. *International Journal of Audiology, 52*(2), 113–123. https://doi.org/10.3109/14992027.2012.733421.

Ziegler, J. C., Pech-Georgel, C., George, F., & Lorenzi, C. (2009). Speech-perception-in-noise deficits in dyslexia. *Developmental Science, 12*(5), 732–745. https://doi.org/10.1111/j.1467-7687.2009.00817.x.