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Research Article

Central Auditory Processing Development in Primary School Children

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Abstract

Objective: The aim of this study was twofold: (1) investigating the development of auditory processing abilities, and (2) exploring the possibility of the clinical application of the test battery used in the study.

Design: The proposed battery aims to test a wide range of central auditory abilities as defined by ASHA (2005) within strict time constraints: lateralization, discrimination (i.e., frequency, duration and intensity), auditory identification, semantic recognition, temporal order judgment, central masking and stream segregation. All tests use nonverbal material to minimize the effect of language development.

Study Sample: Eighty-nine typically developing children from 1st to 5th grade (from 6.7 to 10.6 years old) and 23 young adults were tested on these several auditory tasks.

Results: A developmental effect was revealed in all but one proposed task: stream segregation. Interestingly, developmental trajectories differed depending on the task, with a developmental step and maturation occurring before adulthood for some abilities and linear development leading to maturation occurring during adolescence for other abilities.

Conclusion: This study shows that (1) auditory processes develop during childhood at different rates and in different ways and (2) the battery can test a wide range of them in a relatively short amount of time.

Keywords: Auditory Development; (ASHA) American Speech-Language-Hearing Association; (AEP) Auditory Evoked Potentials; (BSA) British Society of Audiology; Central Auditory Abilities; (SLI) Specific Language Impairment; Typical Development; (APD) Auditory Processing Disorders.

Introduction

Central auditory processes take place at the level of central auditory system, that is, exclude the external, middle and internal ear. According to the American Speech-Language-Hearing Association [1] these processes are responsible for the following behaviours: sound localization and lateralization, auditory

discrimination, auditory pattern recognition, temporal aspects of audition, auditory performance in competing acoustic signals and auditory performance with degraded acoustic signal. Although it is well known that central auditory mechanisms are not mature at birth and continue to develop during childhood [2-4], to our knowledge very few studies got interested in the time course of this development in more than one or two processes [5,6].

Central auditory processing is more usually studied in relation to Auditory Processing Disorders (APD) and their implication in Specific Language Impairment (SLI) and/or dyslexia [7-11]. Consequently, central auditory abilities which are not found to be impaired in population presenting SLI or dyslexia are under-

represented in the literature compared to processes impaired in such population. For example, intensity discrimination seems to be preserved and thus, is not much studied both in children and adult population [12-16]. In contrast, frequency discrimination, which is suspected to be impaired in these populations is over-represented [7,12,14,17,18- 25].

The aim of the present study is twofold: (1) provide an overview of the development of central auditory abilities in typically developing children from 1st to 5th grade (i.e., mean age between 6 and 11 years old) and (2) evaluate the clinical validity of the battery developed.

The children data will also be compared to a group of normal young adults to define mature level of developmental process. In addition, the presented tests are entirely nonverbal as British Society of Audiology [26] recommends, results are therefore less influenced by the literacy skills of participants. Indeed, as language develops importantly and at different rates during childhood, it is of particular interest to present non-verbal stimuli to children; testing APD using verbal material would increase the confound between verbal and auditory abilities. Moreover, a battery testing APD that could be used with children suffering from a language development disorder is needed.

Although peripheral auditory processes are already efficient during pre-natal life and are mature within 30 days after birth, central auditory abilities on the other hand are longer to develop. Auditory cortices mature gradually until adulthood whereas midbrain and brainstem mature during the first years [27]. Sensory encoding of sounds attributes is thus mature only in young adulthood, as reflected by the evolution of the Auditory Evoked Potential (AEP) P1 and N1 (P1 reflecting the synaptic delay between peripheral and central auditory abilities and N1, being evoked in the primary and associative auditory cortices in response to an unexpected stimulus). These two components, reflecting pre-attentive processing, are very robust in adults but not in children and infants [28-31]. These findings suggest that auditory processing mature with age and that they are independent of higher cognitive skills. However, using AEP to investigate the efficiency of central auditory mechanism leads to two difficulties. (1) AEP originates in auditory cortex, and therefore does not reflect brainstem disability and ABR which could be useful appear to have a low sensibility to CAPD [32]. (2) Testing several auditory processes with EEG would be extremely long, and therefore difficult for example in diagnostic situations.

Settings used to behaviourally investigate auditory development are much shorter and easier to adapt for diagnostic and evaluation purposes although they might depend on the integrity and efficiency of higher cognitive skills. This issue will be discussed in the Discussion section. This is why the aim (2) of this study is to evaluate a battery investigating a large part of central auditory abilities and able to provide a reliable cue on auditory processing development using tests adapted to diagnostic situation (i.e., fast, sensitive and easily interpretable). This study is a first step in this direction: testing the battery before it can be normalized on a larger population.

The battery allows testing many auditory processes on the same population, using when possible the same paradigm to evaluate the different dimension of the same process (i.e., auditory discrimination and auditory pattern test). These will allow reliable comparison of the different developmental trajectories. Indeed, looking at the literature on auditory processes development it appears that it is difficult to compare studies as children's performances are very sensitive to the paradigm used. For example, [33] evidenced that children's ability to discriminate frequency varies depending on the paradigm used and for instance on whether the target tone is cued or not, or whether the compared tones are repeated or not (i.e., form a perceptual anchor, [19,34]).

Another issue regarding the comparison between the different studies is the choice of threshold. As mentioned earlier, even if development of frequency discrimination is very well documented [6,7,14,18,22,33] none of the studies use the same paradigm and/or report the same threshold (i.e., 70.7%; 75% or 79%). Our study will therefore enable to compare children of different age's performances and developmental variation across different dimensions. For example, frequency, duration and intensity will be tested using the same discrimination paradigm and the same thresholds, so their developmental trajectories would be comparable.

The objective of our study was double: report developmental course of central auditory processing in school age children and also evaluate the validity of the battery for a clinical application. On this purpose, participants were presented to 6 main tests evaluating central auditory processing, as they are defined by the ASHA [1]. The proposed tests were designed to assess most of the auditory skills listed by ASHA: (1) a lateralization test to evaluate the ability to lateralize a sound, (2) an auditory discrimination test involving frequency, duration or intensity to evaluate the discrimination ability for all sound dimensions, (3) a central masking test evaluating the auditory performances with degraded signals, (4) an auditory identification and recognition test to assess the recognition of an auditory pattern, (5) an auditory pattern recognition test involving frequency and duration aiming at evaluating the temporal aspect of audition, and particularly the temporal ordering, (6) a stream segregation test to evaluate auditory performances in competing acoustic signal.

This test is of particular interest to evaluate the sequential auditory process involved in speech in noise perception.

The development of central auditory abilities was examined by comparing the performances of participants aged from 6 to 11 years old. More precisely, this study will allow us to investigate whether all auditory processes develop in the same way (in term of speed, developmental step, age of maturity) as this would be a cue to underlying processes (i.e., different trajectories would suggest different processing; [2]). A young adult population was also tested for control and as evaluation of the outcome of the early developmental process, it will thus be possible to investigate whether the tested ability is mature by the end of childhood or continue to develop until adulthood.

Method

Participants

The tests were administered to 89 children (37 males). They were classified following their school class from 1st to 5th grade corresponding to chronological age (Table 1). They were recruited in two primary schools and selected by teachers for presenting no developmental disorder. They were all French native speakers and reported no hearing disorder. All of them had normal nonverbal IQ as shown by matrices subtest of the WISC (Wechsler Intelligence Scale for Children; Wechsler, 2005) (Table 1). Non-verbal IQ

did not differ across Group, as evidenced by a one-way ANOVA ($F(4.84) = 1.04, p > .10$).

A group of 23 young adults (18-22 years old; $M = 20.2$; $SD = 1.0$) has also been tested. All adults were French native speakers with audiometric pure-tone thresholds < 20 dB on a frequency range from 250 Hz to 8000 Hz. All of them had a normal non-verbal IQ assessed by Raven standard progressive matrices ($M = 47.9$; $SD = 6.5$; [39]).

Participants reported no history of psychiatric or neurological disorder. Children and their representatives, and adults signed written informed consent. Children were given a diploma of good willingness and adults were compensated for their participation.

	1 st grade			2 nd grade			3 rd grade			4 th grade			5 th grade		
	n	M	SD	n	M	SD	n	M	SD	n	M	SD	n	M	SD
AGE (in years)	18	6,72	0,36	18	7,64	0,36	19	8,53	0,28	15	9,55	0,44	19	10,62	0,46
Matrices score	18	10	3	18	9.7	3.1	19	9.7	4	15	11	4	19	9.2	3

Table 1: Age and matrices scores for children depending on class group (M = Mean; SD = Standard Deviation).

Auditory Tests

Six main tests were presented to participants. Schematic representation of all tests is shown in (Figure 1).

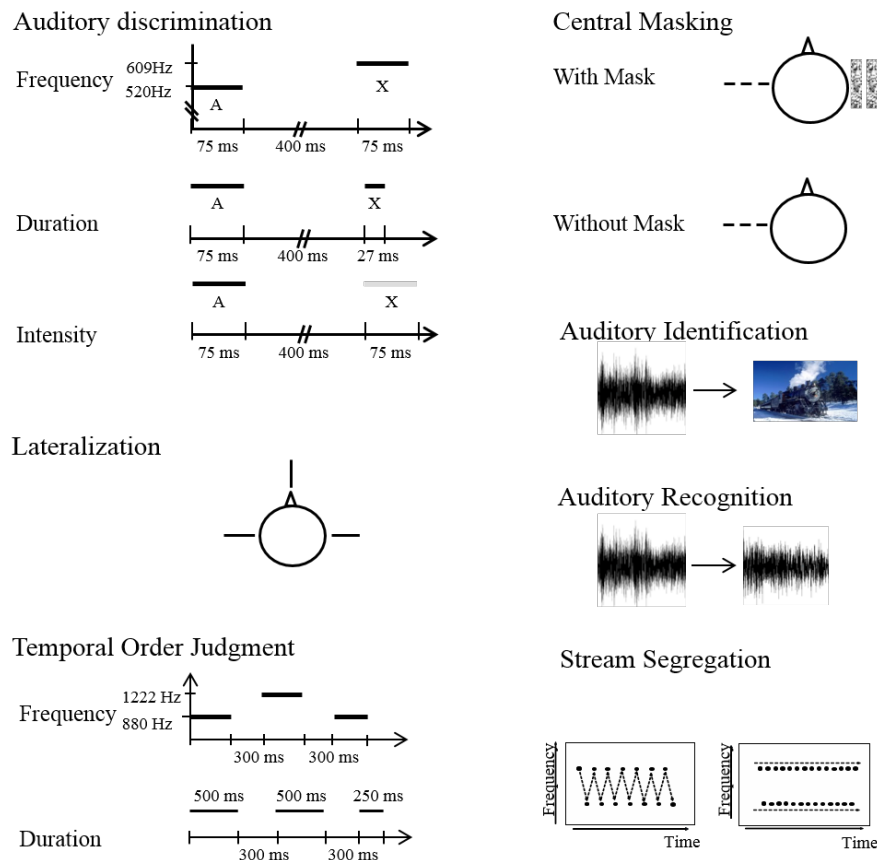


Figure 1: Schematic representation of each test and subtest.

Laterlization

Laterlization skills were assessed by presenting binaurally a pure tone (250 ms; 500 Hz; rise-fall ramps 5 ms) with an Interaural Level Difference (ILD) varying from -5 dB to -25 dB by 2 dB steps (i.e., 11 ILD). Each ILD was presented 4 times (twice with the left ear intensity lower than the right ear's and twice with the opposite configuration). In addition, in 22 trials, stimuli were presented with a 0 dB ILD (i.e., the same level in both ear). This test therefore contained 66 trials. A training session providing a feedback and including 6 trials (2*-25 dB ILD; 2*-5 dB ILD and 2* 0 dB ILD condition) for adults and 12 (2*-25 dB ILD; 2*-21 dB ILD; 2*-15 dB ILD; 2*-11 dB ILD; 2*-5 dB ILD; 2*0 dB ILD) for children were presented. Participants were asked to indicate the origin of the pure tone (i.e., left ear, right ear or the two ears), by pointing the ear where the sound was heard for children and by pressing the corresponding key for adults. No feedback was provided during the test session.

Discrimination

The discrimination test was composed of 3 subtests testing respectively frequency, duration and intensity discrimination abilities. An AX paradigm was presented where participants heard a first pure tone A (75 ms; 520 Hz; rise-fall ramps 5 ms) following by a second pure tone X after a 400 ms ISI. The second pure tone could be the same as the first one or could vary in frequency, duration or intensity depending on the subtest: (1) Frequency discrimination test, X could have a frequency of 527 Hz; 535 Hz; 546 Hz; 562 Hz; 583 Hz; 609 Hz; (2) Duration discrimination test, X duration varied from 27 ms to 67 ms with 8 ms steps (i.e., 27 ms; 35 ms; 43 ms; 51 ms; 59 ms; 67 ms); (3) Intensity discrimination test, X intensity compared to A's varied from -2.5 dB to -15 dB with 2.5 dB steps (i.e., -2.5 dB; -5 dB; -7.5 dB; -10 dB; -12.5 dB; 15 dB).

Each value of X was presented 4 times (i.e., 6 value of X * 4 trials = 24 trials) and X was the same as A in half trials (i.e., 24 trials). Subtests were thus made of 48 trials randomly presented. A training session including a feedback was presented before testing. During this phase 12 trials were presented to children, in half of them X was different from A (i.e., one for each value of X). Adults were presented to 6 training trials, half of them included an X different from A (i.e., the 1st, the 3rd and the last easier to discriminate from A). Participants had to indicate whether the two pure tones were identical or different by pressing a prespecified key.

Central masking

The central masking test was composed of two subtests, a Without mask subtest and a With mask subtest.

In both subtests, 3 pure tones (200 ms; 500 Hz; rise-fall ramps 10 ms) separated by a 200 ms ISI were presented to one ear in half trials. Nothing was presented to the other ear in the Without mask subtest whereas 3 bursts of white noise (i.e., the mask) were simultaneously presented to the other ear in the With mask subtest. The intensity (in dB) of the pure tones ranged from 30 dB to 2 dB

with 2 dB steps, each condition was presented twice for each ear. The mask intensity stayed at 60 dB, therefore in the With mask condition the relative intensity of pure tones was -30 dB to -58 dB with 2 dB steps.

The other half trials were silent in the Without mask subtest, and only contained the white noise in one ear in the With mask subtest. Each subtest contained therefore 120 stimuli presented randomly, given the high number of stimuli and the monotony of the task, a break was inserted after the first 60 trials. Participants were asked to indicate whether or not they heard the 3 pure tones by pressing the corresponding key. Six training trials were proposed to adults and 10 to children.

Auditory identification and recognition

These two subtests are the only one not involving pure tones. Both subtest consisted in presenting a target auditory sequence corresponding to a daily encountered object (e.g., a fire noise). Twenty-eight environmental sounds were presented to participants. One practice item was presented in each subtest. (1) Auditory identification was tested by presenting the subject with sound samples. For each sound samples, three pictures were simultaneously presented to participants. One of them representing the object producing the target sound samples (e.g., a fire), another one representing a semantically (but not acoustically) related object (e.g., fireman truck) and the last one consisted of an acoustically (but not semantically) related object (e.g., crumpled paper). Children participants had to point out the correct drawing and adults had to press the corresponding key. (2) Auditory recognition was tested by presenting a target sound sample (e.g., a starting car) to the subject followed by three sound samples produced by daily encountered objects. One of them was produced by the same object that produced the target auditory sequence (but was not the same sequence; e.g., a driven car), another one was produced by semantically associated object (i.e., a horn) and the last one was produced by an object acoustically related to the target (e.g., a mower). The answer was given in the same way as for the auditory identification subtest.

Auditory pattern recognition

This test was composed of two subtests, one of them assessing the frequency and the other one the duration. Both consisted in the presentation of 3 pure tones separated by a 300 ms ISI. They included a training session containing 10 trials (a feedback was provided by the experimenter for the 5 first trials). After this phase, 20 trials were presented binaurally. Children had to sing or hum the heard sequence, adults had to reproduce it on a piano keyboard, they did not have to produce the exact note, only the relative frequency or duration of the notes were taken into account. (1) Auditory pattern recognition on frequency, the 3 presented pure tones had the same length (500 ms; rise-fall ramps 5 ms) but could vary in term of frequency. They could be 'High' (H; i.e., 1122 Hz) or 'Low' (L; i.e., 880 Hz). Six possible patterns were presented to participants: HHL; HLH; HLL; LHH; LHL; LLH. (2) Auditory pattern recognition on duration, the pure tones frequency was held constant (1000 Hz; rise-fall ramps 5 ms) but

their length could be ‘Short’ (S; i.e., 250 ms) or ‘Long’ (L; i.e., 500 ms). The six following possible patterns were presented to participants: SSL; SLS; SLL; LSS; LSL; LLS.

Stream segregation

The stream segregation test was the same as the one used by [35]. Tone sequences of alternating pure tones of 1000 Hz and 400 Hz were presented to participants for 5 s. Each pure tone lasted for 40 ms (rise-fall ramps 10 ms). Participants had to report whether they perceived one or two streams according to a forced choice paradigm. A training phase was presented to ensure that participants understood the correspondence between the percept and the concept. For this purpose, two practice trials including an unambiguous ‘one stream’ percept (Stimuli Onset Asynchrony, SOA = 400 ms) and an unambiguous ‘two streams’ percept (SOA = 50 ms) were presented and associated with corresponding drawings. After each sequence, children answered by pointing at the drawing corresponding to the pattern they had perceived; adults responded by pressing the corresponding key. The SOA was varied using an one-up, one-down adaptive procedure, to estimate the fission threshold (i.e., 50% chance of hearing one or the other percept; [36]). As long as the answer was ‘one stream’, SOA decreased. On the contrary, as long as the answer was ‘two streams’ the SOA increased automatically. Each session included 30 sequences. The initial SOA (300 ms) was chosen to be perceived as ‘one stream’.

In the first trials, SOA decreased by steps of 40 ms. After the first answer reversal, steps were set to 20 ms, then to 10 ms after the second reversal and 5 ms after the third reversal. Stream segregation threshold was then computed by averaging the SOAs of the last 10 trials (trials 21 to 30).

General Procedure

Children were tested during two sessions in a quiet room at school. They could ask for a break when needed. Lateralization and discrimination tests lasted for about 5 min each (i.e., 20 min), auditory identification and recognition, and stream segregation lasted for 10 min (i.e., 30 min) each and central masking for 15 min. These durations do not include time of break, time to explain tasks and to focus children, and time needed to change and set up experimental tools. Overall, each session lasted about 50 min.

Tests were presented using Super Lab Pro (www.cedrus.com) except for the auditory pattern recognition tasks, and auditory identification and recognition tests which were presented with power point software (2010). The stream segregation test was presented using E-prime2 (Psychology Software Tools, Pittsburgh, PA). Stimuli were presented through headphones (Sennheiser HD 280 pro) at an intensity of 65 dB-A.

Adults were tested in a quiet room at the Laboratory on Language, Brain and Cognition (L2C2). All tests were presented using E-prime2 (Psychology Software Tools, Pittsburgh, PA).

Stimuli were presented through headphones (Sennheiser HD 448) at an intensity of 65 dB-A.

Results

For each test and subtest an ANOVA was performed to evaluate the effect of Development on participants’ performances (i.e., 1st grade vs 2nd grade vs 3rd grade vs 4th grade vs 5th grade vs Adults). Post-hoc analyses (HSD Tukey) were then realized in order to investigate more precisely developmental trajectories. Data are presented in (Table 2).

Data Analyses

Psychometric function

For the lateralization and the discrimination tests, the psychometric functions fitting best each participant’s data were computed. We then computed for each participant the threshold where they were able to lateralize a pure tone or to discriminate two pure tones correctly at 75%. This threshold was chosen because, as mentioned in the introduction, it is very difficult when working with children to distinguish perceptual developmental effect and more general cognitive developmental effect. Therefore, it is possible that some children would answer randomly without really performing the task for example because they were not strongly involved in the task. A 50% threshold would thus not really evidence a perceptual threshold. The aim of computing the psychometric function was (1) to compare our results with developmental literature, and (2) to diminish the impact of non-sensory factors as analyzing the threshold derived from the function decreases the impact of unattended trial. Participants whom 75% threshold did not fall into the extreme value of the test stimuli were excluded from analysis. For each test and subtest, a Chi2 test was performed to ensure that the number of excluded participants did not depend on the developmental group (1st grade; 2nd grade; 3rd grade; 4th grade; 5th grade and Adults). The aim was to evaluate whether younger children were more likely to obtain thresholds not included within the extreme values of the test stimuli. The Chi2 test for the frequency discrimination subtest appeared to be significant showing that fewer adults were excluded from analysis based on their performances. Two adults (the best and the worst performers) were therefore excluded from the analysis of the frequency discrimination test so that the number of excluded participants was not different across developmental group (Chi2 $p > .05$).

Stream segregation test

The stream segregation test was built with an adaptive task; participants were therefore supposed to approach their fission threshold within the last ten trials. Participants who responded more than 5 times “one” or “two” streams in a row during the last 10 trials were considered as not understanding/performing the task and were thus excluded from the analysis.

	1 st grade		2 nd grade		3 rd grade		4 th grade		5 th grade		Adults	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
Lateralization	13.42	4.93	11.76	3.71	10.66	4.28	9.25	2.85	9.49	3.42	9.7	3.81
Discrimination												
Frequency	46.38	20.23	36.97	19.17	46.77	18.93	34.82	20.45	36.41	17.23	17.06	7.34
Duration	31.22	10.63	29.6	9.55	26.79	10.46	19.84	5.36	23.92	7.4	18.5	5.78
Intensity	7.59	3.47	7.18	3.2	7.19	1.96	6.49	2.96	4.75	1.91	3.53	1.51
Central Masking												
With mask												
-50 dB	0.55	0.54	0.75	0.3	0.8	0.21	0.86	0.28	0.8	0.27		
-52 dB	0.56	0.35	0.6	0.29	0.68	0.27	0.74	0.34	0.79	0.26		
-54 dB	0.48	0.35	0.56	0.4	0.56	0.37	0.7	0.32	0.76	0.33		
-56 dB	0.44	0.37	0.5	0.27	0.68	0.29	0.49	0.47	0.62	0.37		
-58 dB	0.3	0.3	0.4	0.41	0.61	0.26	0.5	0.38	0.55	0.42		
Without mask												
-50 dB	0.76	0.24	0.9	0.14	0.9	0.17	0.9	0.17	0.94	0.1		
-52 dB	0.81	0.25	0.75	0.29	0.9	0.25	0.9	0.15	0.93	0.14		
-54 dB	0.69	0.32	0.77	0.25	0.87	0.21	0.85	0.19	0.91	0.16		
-56 dB	0.7	0.28	0.55	0.42	0.85	0.24	0.78	0.27	0.84	0.22		
-58 dB	0.67	0.39	0.62	0.4	0.9	0.17	0.65	0.42	0.84	0.3		
Stream Segregation	140.25	67.12	136.39	86.39	86.62	59.72	150.25	68.4	155.18	86.4	127.51	69.89
Auditory Identification												
Acoustic Errors	3.33	1.64	2.44	1.25	3.21	1.87	1.73	1.28	1.53	1.07	1.39	0.94
Semantic Errors	0.5	0.71	0.83	0.92	0.42	0.69	0.53	0.64	0.47	0.84	0.61	0.99
Auditory Recognition												
Acoustic Errors	7.06	2.65	4.5	1.58	5.37	1.54	4.53	1.92	3.68	2	2.7	1.18
Semantic Errors	1.06	1.06	1.78	0.81	0.79	0.92	0.87	1.19	0.32	0.48	0.91	1.08
Temporal Order Judgment												
Frequency	15.44	4.58	17.44	2.75	17.42	2.69	18.13	2.36	18.84	1.5	19.48	1.12
Duration	10.61	4.33	13.39	2.97	13.58	0.9	15.2	3.43	17.21	2.12	18.35	1.8

Table 2: Mean score (M) and Standard Deviation (SD) for each test depending on the population.

Lateralization

Following exclusion rules (see section 3.1.1.), the analyses were performed on 96 participants. A one-way ANOVA on the 75% threshold comprised between -2.5 dB and -25 dB revealed a significant effect of Development ($F(5,90) = 2.53, p < .05; \eta^2 = 0.12$), younger participants needed a larger ILD to lateralize a pure tone at 75% than older participants. Examining the trajectory of the data, it seems that thresholds tend to decrease from 1st to 4th grade with a slope of -1.36 between the two means of performances ($p = .09; y = -1.36x + 14.76$) and then stabilizes, as shown by a flat developmental trajectory between 4th grade and Adults ($p = 0.99; y = 0.23x + 9.03$) (Figure 2A). This would therefore suggest that maturation of lateralization processing occurs in late childhood, up to 4th grade.

Auditory Discrimination Frequency

Ninety-seven participants had a threshold comprised between 7 Hz and 89 Hz and were therefore included in the analysis. A one-way ANOVA on discrimination thresholds revealed a significant effect of Development ($F(5,91) = 7.35, p < .001; \eta^2 = 0.28$). Younger participants needed significantly higher differences between A and X to discriminate them at 75%. When examining the data, it appears that overall thresholds decrease slightly ($y = -2.21x + 46.89$) without being significantly different ($p = .60$) between 1st and 5th grades. This decrease is more important ($y = -19.34x + 55.75$) and is significant between 5th grade and adult's participants ($p < .01$). Fifth grade participants needed a significantly higher difference between A and X to discriminate them at 75% compared to Adults (Figure 2B). Therefore, it appears that frequency discrimination abilities mainly mature between 5th grade and adulthood.

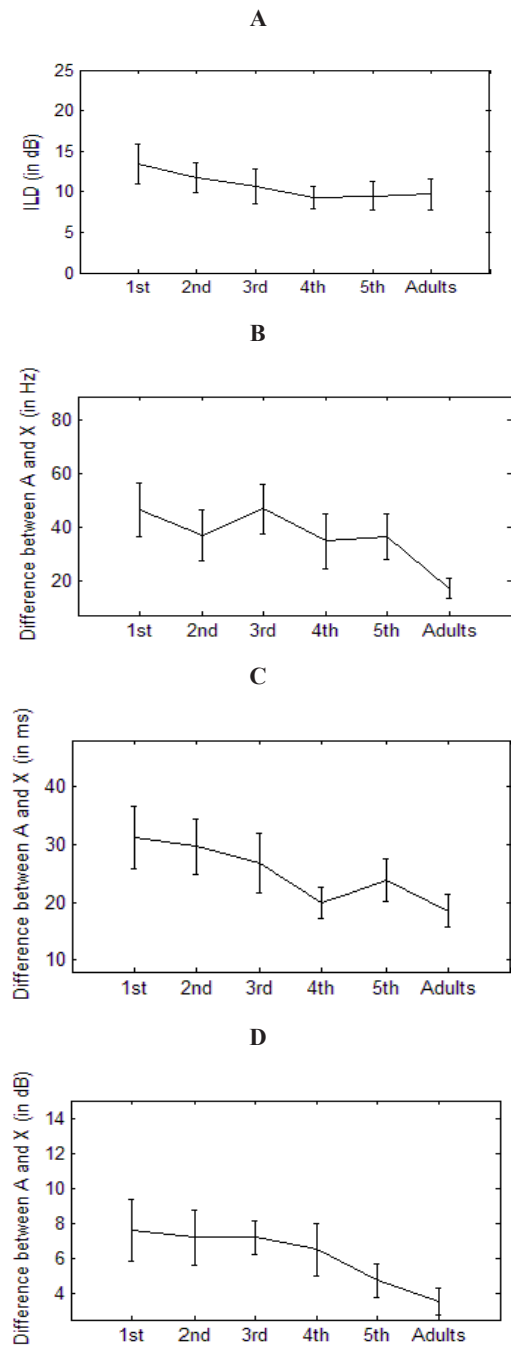
Duration

Thresholds of 100 participants comprised within the extreme values of X (i.e., 8 ms to 67 ms) were analysed. A one-way ANOVA revealed a significant effect of Development ($F(5,94) = 6.36, p < .001; \eta^2 = 0.25$) indicating that younger participants needed a larger difference between A and X to be able to discriminate them at 75%. Data show a decrease in the 75% thresholds between 1st and 4th grade ($p < .01; y = -3.7x + 36.1$) and a stabilization between 4th grade and Adulthood ($p = .99; y = -0.67x + 22.08$) (Figure 2C). Overall these results suggest a maturation of duration discrimination ending in 4th grade.

Intensity

Intensity thresholds of 102 participants, ranging from -2.5 dB to -15 dB were analysed. The ANOVA revealed a significant effect of Development ($F(5,96) = 7.54, p < .001; \eta^2 = 0.28$) suggesting that younger participants needed a greater difference between A and X to discriminate them than older. The developmental trajectory does not seem to be linear.

Indeed, thresholds seems to be stable from 1st to 3rd grade ($p = .99; y = -0.20x + 7.72$) and decreases between 3rd grade and Adulthood ($p < .001; y = -1.27x + 8.67$). It seems thus that the ability to discriminate intensity develops quite lately, since 3rd grade (Figure 2D).



Figures 2(A-D): A. Lateralization test. Interaural Level Difference (in dB) needed for participants to lateralize pure tone at 75% depending on the population. B. Frequency discrimination test. Frequency difference between A and X (in Hz) needed for participants to discriminate them accurately at 75% depending on the population. C. Duration discrimination test. Duration difference between A and X (in ms) needed for participants to discriminate them accurately at 75% depending on the population. D. Intensity discrimination test. Intensity difference between A and X (in dB) needed for participants to discriminate them accurately at 75% depending on the population.

Central Masking

Due to technical issue, data of adult participants could not be analysed. Therefore, only children's performances were analysed. Hit rates (proportion of "present" answers when the Tone was present) and False Alarm rates (proportion of "present" answers when the tone was absent) were computed across all conditions for each participant.

A repeated measure ANOVA was performed on Hit - FA including the between subject factor Development and the within subject factor Mask (With vs Without) and Intensity of the pure tone to detect (10 dB vs 8 dB vs 6 dB vs 4 dB vs 2 dB). Development factor was significant ($F(4,74) = 2.66, p < .05; \eta^2 = 0.12$), older participants had better score than younger. As expected, Mask and Intensity factors were also significant. Participants being less accurate in the With mask subtest than in the Without mask subtest ($F(1,74) = 48.26, p < .001; \eta^2 = 0.39$) and being more accurate at detecting pure tones when they were presented louder ($F(4,296) = 34.82, p < .001; \eta^2 = 0.37$).

Only the factors Development and Intensity had a significant interaction ($F(16,296) = 2.57, p < .001; \eta^2 = 0.03$). Intensity effects are significant only once in 1st grade (2 dB vs 10 dB, $p < .01$), twice in 2nd grade (2 dB vs 10 dB, $p < .01$; 4 dB vs 8 dB, $p < .01$) and then mostly in 4th grade (4 dB vs 10 dB, $p < .01$; 4 dB vs 8 dB, $p < .01$; -58 dB vs -50 dB, $p < .01$; 2 dB vs 8 dB, $p < .01$ and 2 dB vs 6 dB, $p < .01$) and 5th grade (2 dB vs 10 dB, $p < .01$; 2 dB vs 8 dB, $p < .01$).

Auditory Identification and Recognition

Auditory identification

Number of error were analysed with a repeated measure ANOVA, including Development as between subject factor and Type of Errors (Acoustic vs Semantic) as within subject factor.

The effect of Development was significant, younger participants committed more errors than older ($F(5,106) = 5.79, p < .001; \eta^2 = 0.21$). Participants made significantly more Acoustic than Semantic errors ($F(1,106) = 116.76, p < .001; \eta^2 = 0.46$). Interestingly, the interaction between the two factors was also significant ($F(5,106) = 5.79, p < .001; \eta^2 = 0.11$). Indeed, as shown by the data, the number of Acoustic Errors is quite stable between 1st and 3rd grade ($p = 1; y = -0.06x + 3.12$), and decreases significantly between 3rd grade and Adulthood ($p < .001; y = -0.57x + 3.38$). The number of Semantic Errors on the other hand stays stable and very low from 1st grade to Adulthood ($p = 1; y = -0.01x + 0.60$) (Figure 3A).

Auditory recognition

A repeated measure ANOVA was performed on the number of error. It included Development as between subject factor and Type of Error as within subject factor (Acoustic vs Semantic). The effect of Development was significant ($F(5,106) = 23.40, p < .001;$

$\eta^2 = 0.52$), younger participants committed more mistakes than older. All participants made significantly more Acoustic errors than Semantic errors ($F(1,106) = 312.11, p < .001; \eta^2 = 0.63$). The interaction between the two factors Development and Type of Error was also significant ($F(5,106) = 14.39, p < .001; \eta^2 = 0.15$). When looking at the data, it appears that the number of Acoustic Errors decreases with no obvious step from 1st grade to Adulthood ($p < .001; y = -0.14x + 1.46$) whereas the number of Semantic Errors stays stable and low during all development ($p = .90; y = -0.23x + 1.68$) (Figure 3B).

Auditory Pattern Test (APT)

A repeated measure ANOVA including Development as between subject factor and Dimension (frequency, duration) as within subject factor was performed to be able to compare the developmental trajectories. Indeed, it revealed a significant effect of Development ($F(5,106) = 16.36, p < .001; \eta^2 = 0.43$) and Dimension ($F(1,5) = 64.61, p < .001; \eta^2 = 0.35$). In Frequency subtest, younger participants were less accurate than older, as can be seen on Figure 3C, the developmental trajectory does not seem to reveal developmental step from 1st grade to Adulthood ($p < .001; y = 0.72x + 15.28$). The same seems to be true for the Duration subtest, the developmental trajectory does not show any obvious developmental step from 1st grade to Adulthood ($p < .001; y = 1.48x + 9.55$) (Figure 3C).

In addition, participants were less accurate at performing the Duration subtest than the Frequency subtest. The interaction between these two factors was significant ($F(5,106) = 2.6, p < .05; \eta^2 = 0.07$). A post-hoc test (HSD Tukey) showed that only children from 1st ($p < .001$), 2nd ($p < .01$) and 3rd grade ($p < .01$) had lower scores at the Duration subtest than at the Frequency subtest.

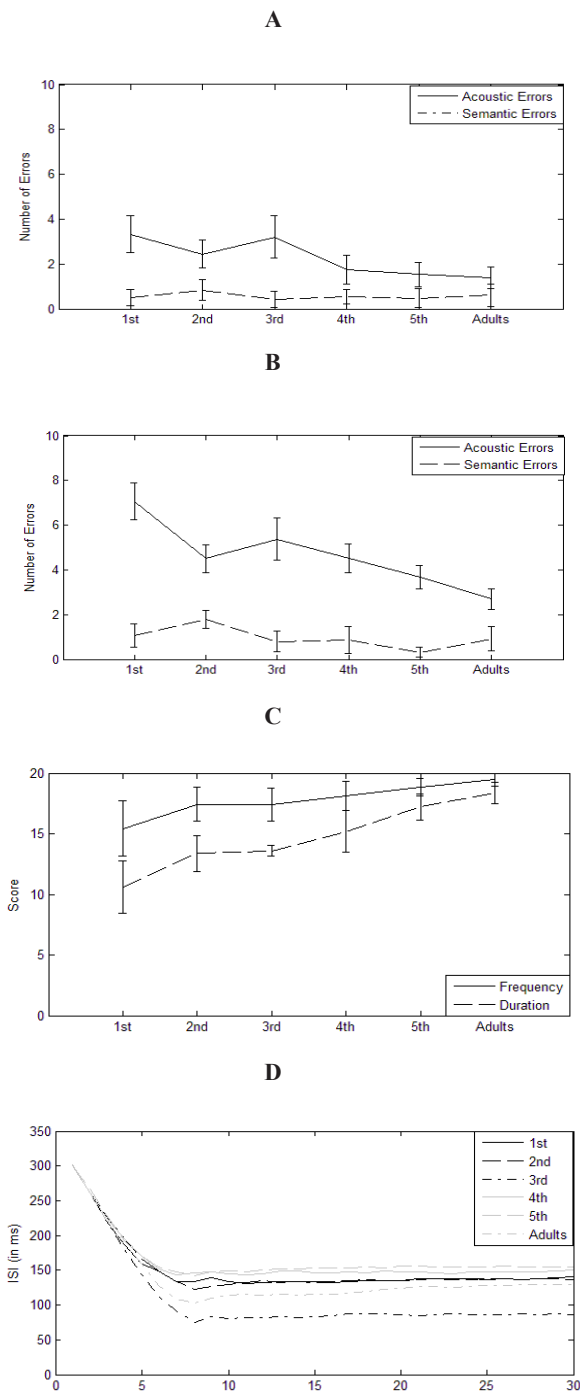
Stream segregation

A one-way ANOVA was performed on the mean of the last 10 trials for 100 participants. The effect of Development was not significant ($F(5,94) = 1.86, p > .05; \eta^2 = 0.09$), suggesting that all participants had the same ability to perform stream segregation based on ISI variation (Figure 3D).

Inter-individual differences

Data of each child was also compared to adult performances. Children's results falling within adult's performances range (i.e., $> \text{Adults mean} - 2 * \text{Adults SD}$) were looked for.

Interestingly, in all but two tests (i.e., frequency and intensity discrimination) more than 50% of children performed within adults' performances range. Every child reached adults performance at least at one test and only two children at only one test (one 1st and one 3rd grade). Four children in 5th grade and 1 in 4th grade showed adult-like performances in all tests. In addition, the mean number of tests where children had adult-like performances increased significantly during primary school as shown by an ANOVA ($F(4,84) = 11.26, p < .001; \eta^2 = 0.42$).



Figures 3(A-D): A. Auditory identification test. Number of Acoustic and Semantic Errors depending on the population. B. Auditory recognition test. Number of Acoustic and Semantic Errors depending on the population. C. Auditory pattern recognition test. Score of auditory pattern recognition depending on the dimension tested, i.e. frequency or duration and on the population. D. Stream segregation test. Evolution of the ISI (in ms) depending on the trial number and population.

Discussion

The aim of this study was twofold: (1) investigate the development of auditory processes in typically developing high school children between 6 and 11 years old and (2) evaluate the possibility of using the battery in clinical situation. A group of young adults was also tested to evaluate the outcome of the auditory development. Six main tests were presented to each participant; they were developed in order to evaluate efficiently and rapidly central auditory abilities. In addition, none of these tests included language and can be used on population with language development disorders. Results will be discussed and compared to literature when possible, to evaluate the validity of our paradigms.

First of all, the lateralization test showed that the ability to use ILD evolves during childhood, and appears to be mature by 4th grade. Indeed, the needed ILD to accurately lateralize a pure tone decreases from 1st (13.42 dB) to 4th grade and then stabilizes around 9 db. No literature measuring lateralization thresholds using ILD in a developmental view was found [37]. However, a very recent study conducted by [38], evidenced that adult listeners needed a mean ILD of 6.2 dB (5.4 dB on one side and 7 dB on the other side) to accurately lateralize a 500 Hz pure tone at 50%. As our threshold was set at 75%, their results seem to be congruent with ours. The ability to use Interaural Time Difference (ITD), was studied by [39] in children from 5 to 9 years old, while no developmental effect was observed during childhood, one appeared between children and adults. These results combined to ours might suggest that the ability to use ILD mature earlier than the ability to use ITD, and thus that cues used to lateralize sounds might evolve during development.

As frequency discrimination depends on the pure tone frequency [27,40], and as studies use pure tones of different frequency, threshold values will be expressed in percent of the standard (e.g., a 30 Hz needed difference between A and X, when A is set at 500 Hz corresponds to a 5.7% needed difference). Our data show that frequency discrimination between 520 Hz and 609 Hz does not significantly improve during childhood. Thresholds however significantly decrease between 5th grade and adulthood (from 7% to 3.3%). This suggests that frequency discrimination matures during adolescence. Our results are congruent with the literature where the needed difference between two pure tones is comprised between 5% and 10% (threshold set at 79% due to the use of an adaptive 3-down/1-up staircase procedure) [11,19,20,22,24]. Although our results are comprised within the literature range, one must note that no significant developmental effect is found in our study, although a significant difference is usually found in the literature. However, frequency processing in higher spectral range seems to be mature earlier than lower ranges [31,42]. It could be that the ability to discriminate pure tones in the tested spectral range (i.e., 520 Hz to 609 Hz) does not evolve during childhood but during adolescence, as shown by the significant difference observed between 5th grade and adults.

Concerning the duration discrimination subtest, as for

previous studies, our data show a significant developmental effect for duration discrimination, confirming that it develops along childhood [42]. In our study, the ability to discriminate duration appears to improve between 1st (31.2 ms; 41.6%) and 4th grade (19.40 ms; 26.4%). It then stabilizes until adulthood (18.45 ms; 24.6%). Overall this pattern is coherent between studies, even though the duration of the standard used is very different as we used shorter pure tone than other studies (75 ms vs 400 ms for [15] or 200 ms for [20]) in order to tackle durations closer to temporal variation in speech (e.g., Voice Onset Time, VOT). However, while in all studies adults' thresholds seem to converge around 20 ms, the results observed for children are more variable. This suggests that children's ability to discriminate duration depends on the duration of the stimulus: indeed, a 20 ms difference on a pure tone lasting for 75 ms is much more noticeable than on a 400 ms pure tone. Maturation seems to lead to a threshold more independent from the stimulus length in adulthood.

Our intensity discrimination subtest shows no developmental effect between 1st (7.59 dB) and 3rd grade (7.19 dB) and then, a decrease between 3rd grade and adulthood (3.53 dB). As mentioned in the introduction, very few data were found on development of intensity discrimination. However, in line with our results, a study by [13] revealed that children from 5 to 10 years old need, on average, 6.7 dB to accurately discriminate 500 Hz pure tones at 70.7%, whereas adults needed 1.5 dB only. The central masking test aimed at investigating whether the processing of a pure tone would be disturbed by the presence of a simultaneous mask in the contralateral ear. Results evidenced that the ability to detect a pure tone increased across development. However, although all participants were less performant in the masked subtest, it does not seem that the effect of masking evolves during development. The lack of data from adults prevents us to state whether sensitivity to a contralateral masker is mature before 1st grade or whether it matures during adolescence. Further investigations are needed to answer this question.

The auditory identification scores showed that the ability to pair a daily encountered sound to a picture without explicitly using language evolves during childhood. Interestingly, the number of acoustic errors is stable from 1st (3.33) to 3rd grade (3.21) and then decreases until adulthood (1.39) whereas the number of semantic errors does not evolve during childhood and during adolescence. This means that the improvement relies on auditory processing efficiency per se and not on the knowledge of concepts. Indeed, participants need to know and be able to recognize the presented concept as the association between an object sound and its picture implies that the object is recognized. The auditory recognition test highlights that participants were able to match two different sounds produced by the same object or living being without visual support. This ability evolves during primary school, while once again, semantic errors did not decrease during development and stay constant. This suggests that participants' scores increase due to a better auditory recognition process. The auditory pattern recognition tests aimed at evaluating the ability of children to perceive, remember and reproduce sequences of three pure tones

differing on one dimension (i.e., frequency or duration) without oral verbalization.

In the frequency subtest, performances increased linearly, with no obvious developmental step, to reach a quasi-perfect score in adulthood. Results obtain at our frequency subtest are around 20% better than those reported by [43] with the Frequency Pattern Test FP, [44]. However, there were several differences between the used paradigms that could explain these differences. First of all, the duration of stimuli is longer in our frequency subtest than in the FPT. The rhythm of presentation is therefore slowed down and might easier the task. Second, the number of trials is smaller, one can assume that participants are less tired, more focused and thus are more performant in our test. Finally, the last difference is the fact that participants in FPT paradigm are required to answer verbally to the test, whereas they were asked in our subtest to hum or sing the sequence for children and to reproduce it on a piano keyboard for adults. The intervention of verbal ability in this test might help explaining lower performances in FPT, because children could easily have difficulties remembering which word corresponds to which percept (particularly as 8 years old children might not be very familiar with 'high frequency' and 'low frequency' concepts). However, although the observed performances are better than those reported on the FPT, the two developmental trajectories are similar, with an increase of performances during primary school and maturation occurring around 10 years old. It seems thus, that after 10 years old the ability to judge, retain and recall a frequency pattern is mature.

The duration subtest was developed in accordance with the Duration Pattern Test [44]. Children's performances increase regularly with age from 66% at 7 to 92% in adulthood. Again performances in our study are slightly better than those reported with the DPT [45,46]. The difference observed between the two set of data is very large around 7 years old (25% correct answers compared to 66% in our study) and much smaller around 10 (70% vs. 86% in our study). Adults on the other hand, seem to perform equally in our test and in the DPT [47]. The number of trials, the ear of presentation (both ear in our test vs one after the other in FPT and DPT) and the type of response differed between the two paradigms and can certainly explain the differences in performances. However, developmental trajectories for both tests seem to be equivalent with a regular increase from childhood to adult age.

The stream segregation task did not reveal any significant developmental effect. Although it is known that stream segregation occurs very early in development [48]. It seems that segregation competences do not evolve during childhood and adolescence, at least when using ISI as cue for segregation. [35] using exactly the same paradigm as us) already evidenced that the ISI corresponding to the change of percept (1 stream vs 2 streams) does not evolve between 10 years old good reader children and normal adults. In the light of our results it therefore seems that stream segregation based on ISI variation is mature as soon as 1st grade. However, as for lateralization abilities, it is possible that cues used for segregating streams efficiently change during childhood, for example [4] found

a developmental effect on stream segregation task using frequency as cue for segregation.

Overall, our results show that development of central auditory abilities in children is neither homogenous nor linear. They also confirm that its development is long lasting. Indeed, only 3 of the tested processing are mature before the end of childhood (i.e., lateralization, duration discrimination and stream segregation). Other tested processes reach adult efficiency during adolescence. While these trajectories are of mere interest, it has to be underlay that development of central auditory abilities is also very variable across children. For example, 6 children (2 in 4th grade and 4 in 5th grade) reached adult level for almost all tests.

Despite these interesting results, our study meets some limits. First of all, the high variability of children's performances also highlights the question of the impact of non-sensory factors [24]. Indeed, an issue raised when working on children development is whether the data reflect sensory or non-sensory factors. Children indeed present lower cognitive abilities than adults; a lack of attention and working memory could explain the observed differences when comparing children to adults. When studying development one main question is therefore whether developmental effect originates in part from attentional and cognitive differences between younger and older children but mostly how much of the results can be explained only by non-sensory factors [6,22,24,33]. Interestingly, in our study, developmental trajectories are different despite different dimensions of the same process were tested using the same paradigm (i.e., discrimination test; auditory pattern recognition test). It therefore suggests that the observed developmental effects do not only rely on cognitive development [6] but on auditory developments per se.

Another limit that should be highlighted is that, despite its ambitious aim of investigating the development of a wide range of auditory processes, our battery does not evaluate all auditory processes.

Indeed, the evaluated frequencies are quite low, and it is known that processing of high and low frequencies are different and mature at different ages [6,20,22,25,27] therefore it could be interesting to also evaluate a higher frequency range. In addition, other auditory processes could be investigated like dichotic listening or sound localization (i.e., in our lateralization test, sounds origin is distributed on a plane, not in a 3D space). However, these limits reach the second aim of our study, that is, setting up and evaluating a battery which can be used in clinical situation. Adding new test would be very interesting but would lengthen its administration.

Another remark that could be made on our battery is that some tasks need different processing to be performed. For example, in the Auditory Pattern Test (both in frequency and duration subtest) an efficient working memory is necessary to perform the task; therefore, poor performances at these subtests could be attributed to a defect in working memory. However, as each stimulus contains only 3 pure tones, this seems highly unlikely.

Finally, as other studies have shown, auditory processes start

to develop before the age of 6 [40,41,49-51]. Currently, our battery is not suitable to be administrated to toddlers or infants; using appropriate paradigm like head-turned paradigm on a younger population could allow us to report the complete development of auditory processes. Future studies could develop this aspect.

Conclusion

The first aim of our study was to evaluate the development of central auditory abilities from 6 to 11 years old. Children's performances were also compared to adults' to evaluate the outcome of development. The second aim was to evaluate the use an entirely non-verbal battery sufficiently brief to be used in a diagnostic situation. An entirely non-verbal battery was thus developed, using only pure tones and daily encountered noises. Results show a developmental effect for all tasks except stream segregation. Development appears to be non-linear with developmental step differing across different tests and subtests. Except stream segregation test which did not reveal any development effect, only two tested abilities appeared to be fully mature during childhood: lateralization based on ILD and duration discrimination. The other tested abilities appeared to pursue their development during adolescence confirming that auditory development is a very long lasting process.

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