Evaluation of Cognitive Processes using Synthesized Words: Screening of Hearing and Global Speech Perception

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Abstract: This study focuses on children's cognitive capability within the framework of cognitive infocommunication. Speech processing works in quasi-parallel in time between hearing and speech comprehension. Hierarchical operations are decisive for elaboration of the speech signal. To test children's speech processing quickly and reliably is of great importance both for language acquisition and for learning to read and write. Specific speech synthesis using sufficient, but not redundant spectral cues highlight hearing and global speech perception processes. 644 monolingual Hungarian children aged between 4 and 8 years participated in the study. 20 monosyllables were specially synthesized based on a set of pre-determined spectral values. Children were asked to repeat what they heard. The combination of speech synthesis as information and communication technology with the study of cognitive capabilities is a new direction in research and practice. Our results show that the great majority of children were confirmed to have good hearing (about 95%), while some children had a previously unknown hearing impairment. More than 30% of all children encountered speech perception deficit, despite good hearing. Digital technology including speech synthesis has reshaped both speech science and its cognitive connections to get closer to a proper interpretation of the mechanisms analyzed.

Keywords: synthesized speech; frequency cues; cognitive processes; evaluation of speech processing

1 Introduction

This study focuses on the cognitive capability of children within the framework of cognitive infocommunication (CogInfoCom). CogInfoCom intends to provide a systematic view of the interaction between cognitive processes and infocommunication devices and methods in order to show an emerging new concept toward practically unknown research directions [1, 2, 3]. In accordance with the basic concept of CogInfoCom, the present research reports on the realization of the synergic combination of cognitive operations and a specific engineering technology. Our research belongs to "inter-cognitive communication" [3] where information transfer occurs between a human and an artificial cognitive system. The "humans" in our case are children capable of processing acoustic waveforms of speech through their hearing and speech perception mechanism. While the artificial cognitive system is represented by specifically synthesized speech segments that are able to reflect the operations of human speech processing. Such interaction is impossible in human–human communication since human speech is (articulatorily and acoustically) overinsured in order to be processed under various, even noisy circumstances. We intend to connect these two entities in order to develop a very useful application as a compact sytem for practice containing different sensory modalities.

Higher cognitive operations during speech processing are based on age-specific hearing level and appropriate speech perception processes. Although speech processing works in quasi-parallel in time between hearing and speech comprehension, hierarchical operations are decisive for processing the speech acoustic signal [4]. If the child's hearing is good, typical language acquisition processes are expected to take place; however, in cases of hearing impairment speech processing will not develop appropriately, the speech perception mechanism will work with uncertainties, and some sub-processes will show disorders [5, 6]. If the child's speech perception mechanism is good, and it works according to the child's age, no deficiencies are expected with verbal speech comprehension and speech communication [7]. Hearing, verbal speech perception and speech comprehension are responsible for obtaining the necessary information transmitted verbally. Children's successful learning to read and write is partly based on age-specific speech processing including hearing, speech perception and comprehension [8, 9]. Irrespective of the type of communication – verbal or written – appropriate speech processing is of great importance in order to learn and process various kinds of information from the surrounding world.

Despite various types of methods for testing hearing level, including objective auditory examinations like auditory brainstem evoked potentials or frequency-specific auditory evoked potentials [e.g., 10, 11, 12, 13], there are children who have undiscovered mild hearing impairment or serious hearing loss in one or both ears resulting in undesired consequences for typical acquisition of speech perception and comprehension. Testing children's hearing using pure-tone audiometry has limitations and the outcome is frequently unreliable for several reasons [14, 15]. In addition, children usually do not complain of hearing difficulties (they may not realize the reason for their communication problems at certain ages), and adults frequently identify children's behavior as having attention deficit instead of recognizing hearing difficulties.

Even slight hearing loss influences the speech perception processes, particularly during language acquisition. Inappropriately heard frequency patterns of speech sounds will result in inappropriate recognition of their quality. In addition, speech perception difficulties can also arise in case of normal hearing with or without known reasons [16]. Speech perception deficit may cause long-lasting difficulties in communication and learning. Based on experiences and facts, an easily usable, quick and reliable method for screening the children's hearing and recognition ability concerning frequency cues of speech sounds seems to be relevant from the aspect of info-communication. Recognizing the speech sounds in a sound sequence (irrespective of its being a meaningful or a meaningless item) requires various processes, and particularly the identification of frequency patterns [4, 16]. The term 'global speech perception' will be used for identifying these processes.

The goal of this research is to learn reliable data about children's hearing and global speech perception focusing on the identification of frequency cues of the speech sounds between the ages of 4 and 10. We suppose that the GOH hearing screening device is appropriate to fulfil our demands and will provide us with useful results in a quick and reliable way [17]. Quickness and reliability are core factors in our days together with a screening possibility that does not require the child and the parents to go to a certain place (e.g., a clinic), instead, the screening procedure can be applied at homes, in kindergarten and at schools.

Our main research question is whether children of ages between 4 and 10 really show mild or more serious hearing and/or global speech perception deficiencies that are unknown for their adult environment. We have formed three hypotheses: (i) there would be children to show unknown hearing and/or global speech perception deficits irrespective of their age, (ii) no differences would be found in the correct responses between the left and right ears, (iii) a developmental tendency would be shown for increasing correct answers of children across ages.

2 Methodology

2.1 Synthesized Speech Method

The method is based on the insight that specifically synthesized speech containing far less acoustic information than natural speech does would be suitable for the screening of hearing and global speech perception in populations that are difficult to test using traditional procedures [16, 17]. Naturally produced speech is obviously inappropriate for hearing examination since human articulation of speech sounds and sequences of speech sounds leads to complex and redundant acoustic information in relation to frequency, intensity and temporal patterns [18, 19]. However, the frequency structure of synthesized speech can be artificially altered in order to contain less frequency information than natural speech does along with unaltered intensity and temporal characteristics. If synthesized speech sounds contain only, or just slightly more information than the language-specific invariant features – in our case, frequency cues –, they can be successfully used for hearing and global speech perception testing [20, 21].

The question arises how such specifically synthesized words may function to show hearing losses and/or global speech perception deficiencies? If someone has some hearing loss at some frequencies, this person will identify the frequency bands of the heard speech sounds according to their existing hearing capacity [22]. Opposite to naturally articulated speech (that can be flawlessly processed up to a certain degree of hearing loss), specifically synthesized words would not provide redundant frequency elements to serve in speech processing. For example, the consonant [s] can be identified also in the case of high-frequency hearing losses above 5,000 Hz since the remaining frequency elements at around 4,000 Hz would be sufficient for the hearing-impaired person to identify the target consonant. However, if this consonant contains an intensive frequency band only at 8,000 Hz, this hearing impaired person would be unable to identify the target consonant [23, 24].

We have defined the invariant frequency cues for those speech segments that were intended to serve for the monosyllables of our speech material [24]. For the vowels, two formants were defined, for the consonants specific frequency bands were defined depending on the types of the consonants that identified them unambiguously in speech sound identification. For example, Hungarian [s] has characteristic turbulent noises between 4,000 Hz and 8,000 Hz according to its actual articulation. However, fricative consonants containing various frequency bands alone within this frequency range would be identified by Hungarian speakers as the alveolar, unvoiced fricative consonant ([s]). They will be different only according to their timbre. Therefore, three types of [s] were synthesized for the GOH material: one of them contains a frequency band at 4,000 Hz, one at 6,000 Hz and one at 8,000 Hz. They all sound as the required fricative consonant and are identified as realizations of the /s/ phoneme irrespective of their timbre differences (Fig. 1). Speech synthesis was carried out using the OVEIII speech synthesizer providing the pre-defined data [23], and the perceptually confirmed acoustic cues of the target Hungarian speech sounds controlled by a computer.

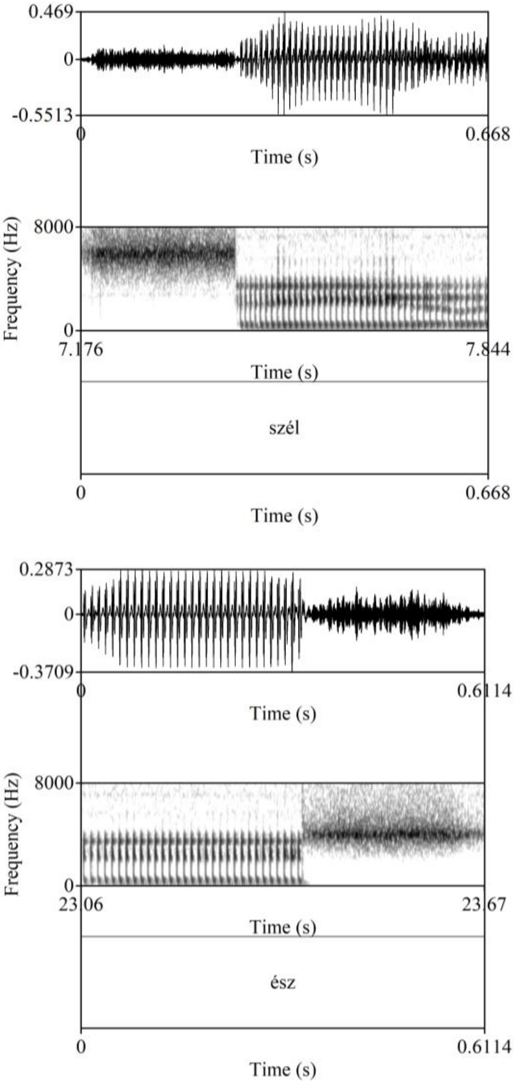
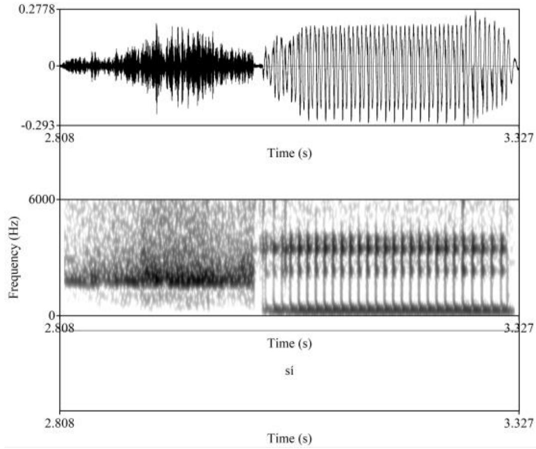
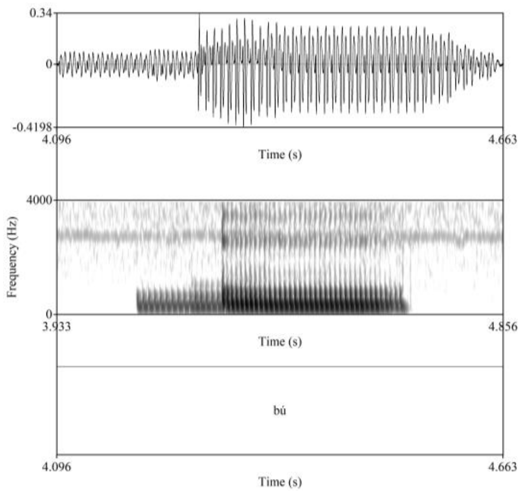


Figure 1
Acoustically different [s] consonants: in the words *szél* ‘wind’ (top) and *ész* ‘wit’ (bottom)

The speech material of the GOH method contains four sets of Hungarian monosyllables where each of them consists of either two or three segments (a vowel and a consonant, or a vowel and two consonants preceding and following the vowel: CV and VCV type words). Each set included 10 words. Four words in each set contained high-frequency bands as acoustic cues like in the word [ʃiː] ‘ski’). Here, the initial consonant has an intensive frequency band at 2,000 Hz while the vowel’s decisive frequency cue appears also at 2,000 Hz as its second formant. Another four words contained speech sounds that have only low frequency bands like in the word [buː] 'sorrow'). Here, the characteristic frequency cue of the initial consonant is at 500 Hz while the second formant of the vowel is at 800 Hz. The remaining two words in each 10-word set contained speech sounds having characteristic frequency bands at both high and low frequencies like in the word [mɛɟː] 'cherry'). Here, the characteristic frequency feature of the initial consonant is around 800 Hz while that of the final consonant is at 6,000 Hz. The second formant of the vowel is placed at 1,700 Hz (Fig. 2).





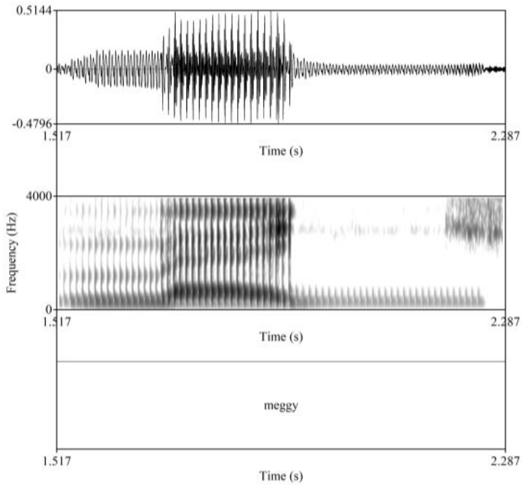


Figure 2

Synthesized monosyllables consisting of characteristic frequency cues sufficient for recognition: the word *sí* 'ski' containing mostly decisive high frequency bands (top spectrogram), the word *bú* 'sorrow' containing mostly decisive low frequency bands (middle) and the word *meggy* 'cherry' containing both decisive low and high frequency bands (bottom)

Most of the words selected for the speech material are familiar to children of ages between four and ten intending not to cause extra cognitive difficulties when processing the test words. However, there are words that are purposely meaningless for the children (like *bók* [boːk] 'compliment'). The mental lexicons of the children across ages are extremely different and also limited in a way [25]. There are no criteria to find words that are familiar for all children. However, during language acquisition, children are used to hearing and processing unfamiliar words when learning new ones to widen their mental lexicon. In addition, the task that is required from the children during testing is simple enough and used in their everyday life: repeating what they have heard.

Previous experiments and investigations using specifically synthesized monosyllables to examine children's hearing capacity and age-specific global speech perception confirmed that the method is appropriate to use with children from as young as 3-year-olds [16, 17]. Therefore, a device has been developed (Fig. 3) that contains the specifically synthesized monosyllables in digital form to test children's hearing and global speech perception processing reliably and quickly. This compact device (15x10x4 cm) contains the synthesized speech material with a touchscreen keyboard and switches for (i) left ear/right ear selection, and (ii) two preset intensity values (45 dB and 55 dB). The former one can be used in clinical settings while the latter one in a silent but not clinical environment. There is also a set of headphones attached to the device.

Figure 3
The GOH screening device based on specifically synthesized monosyllables

An answer sheet – based on the answers of thousands of both normally hearing and hearing impaired children – was created to use the device simply. There are four columns in the answer sheet indicating four levels of hearing capacity and global speech perception: (i) normal hearing, typical speech perception, (ii) normal hearing, speech perception deficit, (iii) mild hearing loss, (iv), hearing loss (at about 40 dB or more). The examiner marks the child's response on the answer sheet either by underlying the word or sound-sequence written on the sheet or, by writing down the actual answer of the child indicating the tested ear (Figure 4). If the child's answers (be they real words or meaningless ones) are the same or similar to the ones that are written in the second column, his/her global speech perception would be impaired but the hearing is normal. If the child's answers are to be marked in the third and fourth columns, his/her hearing would be impaired.

	I. Normal hearing	II. Speech perception deficit	III. Mild hearing loss	IV. Hearing loss
0.	meggy	begy legy negy vegy	egy ety eny	bó od e ó
1.	síp	sít sűt süp szíp szép	zúg suk sut su só fut hó	kút út tú ú
2.	bú	dú bók bot bó pók pú púk dú	tú tó pú pó út	ó ú –
3.	ász	ház pász áz	ás ágy áll áj	áf át á ó ú
4.	bot	but böt bó bu	pot put po pu ot ut	ó ú –

Figure 4
Part of the answer sheet for the GOH hearing and global speech perception screening device illustrating the examiner's markings that show the tested child's answers

2.2 Testing Children with GOH Screening Method

644 monolingual Hungarian children aged between 4 and 8 years participated in the experiments (half of them were girls in each age group). Participants formed five groups depending on age. There were 48 four-year-olds, 166 five-year-olds, 154 six-year-olds, 102 seven-year-olds, and 174 eight-year-olds. All of them had typical onset of their language development (between 12 and 20 months of age), and a typical process of language acquisition according to the parents' statements. They had no known history of speech and language difficulties of any kind. The great majority of the tested children were right handed. All participants came from large towns and had a similar socio-economic status.

The specifically synthesized words were administered to the children through headphones, one ear at a time. Children were asked to repeat what they heard. Each child had to repeat 10 words administered to the left ear and another 10 words administered to the right ear. All children heard the same 20 words. The examinations were carried out in the mornings at the children's kindergarten and school in a silent room (using an intensity level of 55 dB). The scores of correctly repeated words were calculated for each child and for each ear. The amount of correctly identified monosyllables were analyzed according to the children's age and the four levels of evaluated hearing and speech perception. Dependent factors were the numbers of the correctly repeated words while independent factors were ear (left vs. right), age (from 4 to 8), performance level (I. normal hearing, typical speech perception; II. normal hearing, speech perception deficit; III. mild hearing loss; IV. hearing loss). Statistical analyses were carried out by Generalized Linear Mixed Models and paired sample *t*-tests (as appropriate) using SPSS 20.0 software.

3 Results

The number of words correctly repeated by the children showed a significant increase across ages (Figure 5). This means the scores children reached in cases of good hearing and age-specific global speech perception. Good performance is similar in 5- and 6-year-olds while there are steep increases between the ages of 4 and 5 as well as between 6 and 7 and 7 and 8 years. Cognitive processes are quickly developing after the age of 4 including global speech perception [e.g., 7]. Learning to read and write requires age-specific cognitive operations that also have an effect on the identification of speech sounds. These interrelations are reflected in the higher correct scores in schoolchildren.

The correct scores in both the left and right ears are shown in Figures 6 and 7. As expected, kindergarten children recognized the specifically synthesized words less successfully than schoolchildren did. As better auditory-phonetic skills are acquired, spectral patterns of segments can be more successfully used by children.

However, no significant differences were found in correct repetitions of the synthesized words depending on ears in either age group.

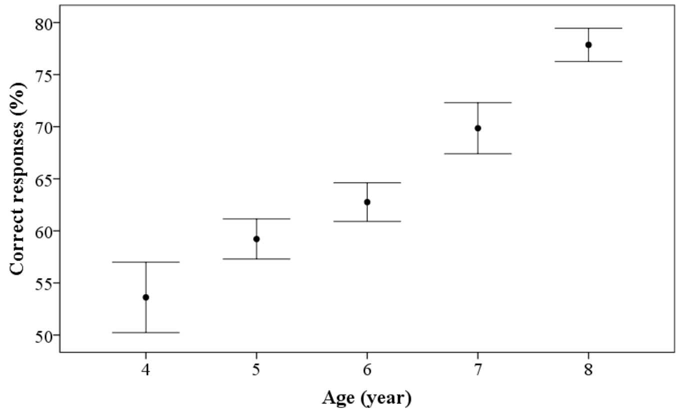


Figure 5
Correct responses of children aged between 4 and 8 for specifically synthesized words (medians and ranges)

Summarizing the correct responses administered to bothears shows the values of 53.6% (SD = 16.5) for 4-year-olds, 59.2% (SD = 17.8) for 5-years-olds, 62.8% (SD = 16.5) for 6-year-olds, and 69.8% (SD = 17.8) for 7-year-olds. The 8-year-olds reached the highest performance of 77.9% (SD = 15.1). Statistical analysis revealed that there was a significant difference in correct responses of children depending on age ($F(4, 1284) = 21.236$; $p < 0.001$). Analyzing the data separately for the two ears, statistical results confirmed significant differences in correct responses both in right $F(4, 640) = 8.301$; $p < 0.001$) and left ear ($F(4, 640) = 6.938$; $p < 0.001$) across ages.

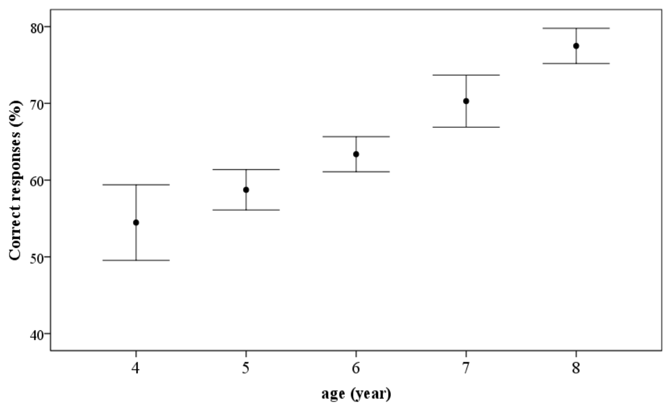


Figure 6
Correct responses of children aged between 4 and 8 for synthesized words heard in their right ear (medians and ranges)

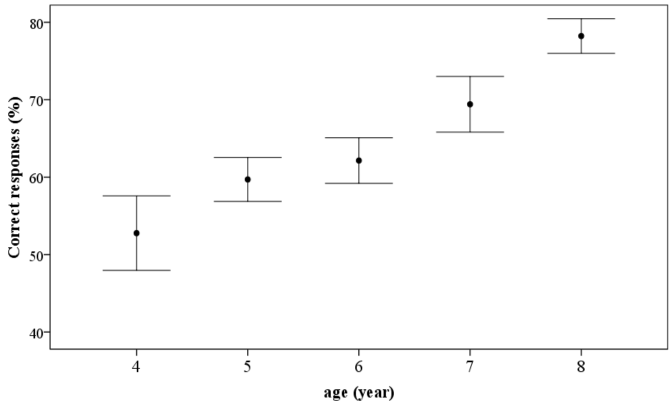


Figure 7
Correct responses of children aged between 4 and 8 for synthesized words heard in their left ear (medians and ranges)

We expected to experience some consequence of right-ear-advantage [Hugdahl] appearing in slightly more correct responses for words administered in the right ear of right-handed children, at least in the case of schoolchildren. However, no ear preference could be found. The explanation for this finding may be that the non-redundant frequency structure of the specifically synthesized words requires similar operations in feature processing irrespective of ears. In addition, to show right-ear-advantage specific dichotic tests are used [26, 27] that are basically different from our present methodology.

Since children's responses can fall in three different columns representing various erroneous answers (apart from the correct response column), this provides the opportunity to evaluate the hearing capacity and global speech perception level with each child. The majority of the children showed age-specific hearing and global speech perception. Figure 8 shows the ratios of children in terms of the four columns (from good hearing and appropriate global speech perception to various levels of hearing loss).

Data shows that the number of children having good hearing and age-appropriate global speech perception seems to be similar across ages. However, 6-year-olds show poorer performance than all the others: fewer children had correct answers and more children showed speech perception deficits in the identification of speech sounds based on their frequency cues than those in the other age groups. Their results predict difficulties in acquiring reading and writing at school.

The children of the two youngest groups outperformed the older ones. What is particularly interesting here is that fewer 7- and 8-year-old children showed good performance than 4- and 5-year-olds. This finding can be explained by two reasons. The more complex speech perception mechanism of the older children than is supposed to exist with the younger ones, may make some of the subprocesses work inappropriately with some children. The other reason could be an increase of the number of children showing inappropriate speech perception development after the age of five.

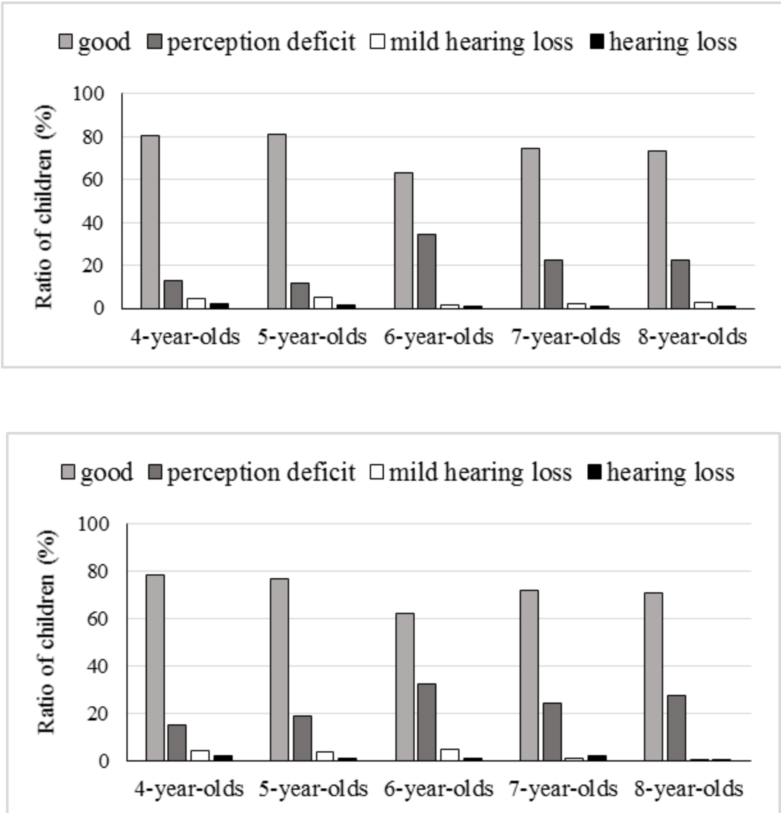


Figure 8

Distribution of children according to the hearing capacity and global speech perception deficit: Ratios for right ear (top) and left ear (bottom)

Global speech perception deficits were found rather in the case of left ears than in the case of right ears across ages. More children were found with hearing loss in the younger population than in the older ones. None of the children was found to have hearing losses in both ears. Statistical analysis showed significant differences between the responses falling in different columns (I. and II.: t = 11.388, p = 0.001; II. and III.: t = 6.966, p = 0.001; as well as III. and IV.: t = 3.531, p = 0.006). No gender differences could be confirmed in the number of correctly repeated words in either age group.

Conclusions

Digital technology including speech synthesis has reshaped both phonetics/speech science and its cognitive connections. Research results of basic communication abilities like hearing, segment recognition and overall speech perception using good quality artificially synthesized speech opened new vistas in a proper identification of these processes. At the same time, these findings heavily influenced the development of speech synthesis resulting in valuable convergence of the two entities.

Our findings support the idea that specifically synthesized words are appropriate for the evaluation of both hearing capacity and global speech perception (primary frequency cues of the speech sounds) in non-clinical settings. We did not expect the result that altogether more than 4% of all children showed mild or serious hearing losses (either in right or left ear) requiring audiological attention. This means that about 35 children out of 644 who were supposed to have good hearing showed some hearing deficit. The covert processes of speech perception showed even more trouble with the tested children. More than 20% of the children had some kind of speech perception deficit that hampers their age-specific recognition of speech sounds and sound sequences and that was unknown until the testing.

Good hearing and age-specific speech perception processes are responsible for communication and for learning to read and write. Therefore, these deficits will impede successful performance at school. The GOH method using specifically synthesized words is appropriate to evaluate the hearing capacity and global speech perception of children providing information on their cognitive operations decisive for reading, writing and learning.

According to the definition of CogInfoCom [3], it combines infocommunication and cognitive science in various ways including diverse cognitive and sensory contents. Our present study describes a blended method of studying the human perception capability and employing digital speech technology that has diverse modalities for further developments in practical applications. Such studies are interpretable only within the interdisciplinary framework of CogInfoCom.

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