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MRI in linguistics and its applications: interdisciplinary approach

Аннотация: В статье говорится об использовании передовых медицинских технологий в исследовании коммуникативной деятельности человека, а именно: об использовании магнитно-резонансного томографа (МРТ) в лингвистических исследованиях. Созданные на основе полученных даных приложения успешно применяются для анализа восприятия речи и речепроизводства, при изучении иностранного языка и обучении языкам, для моделирования, синтеза и распознавания речи, а также в медицине, демографии, антропологии и др. науках.

Ключевые слова: лингвистика, фонетика, прикладная лингвистика, восстанавливающая терапия и реабилитация, МРТ, фМРТ

Abstract: The paper follows main directions of modern interdisciplinary research in linguistic studies realized with the capabilities of MR equipment (MRI). It presents most important achievements of such research for Humanities in general, with the special focus on its linguistic applications. The main areas of MRI employment in linguistic research and in applied research under investigation are: research in speech perception; research in speech production; research for applied linguistics – primarily for educational applications (language learning and language teaching); research for computer-based speech processing engineering applications (speech synthesis and speech recognition); research for needs of health-impaired therapy and rehabilitation; research for various areas in social sciences (demography, anthropology, etc.)..

Keywords: Linguistics, Phonetics, Applied linguistics, Health-impaired therapy and rehabilitation, MRI, fMRI

Introduction

A perennial challenge in speech communication research (both its production and perception aspects) is the ability to examine real-time functional changes in human body behaviour during communication act. The focus of interest was usually either on human brain activities during speech planning and speech production processes, alongside with speech perception and speech understanding procedures, or on the workload of artuculatory “machinery” emerging through transformative shaping of the vocal tract and speech dependent muscular activity in the main human articulators (tongue, lips, uvula, larinx, etc.). In the last three decades it's the advances in magnetic resonance imaging (MRI) techniques that provide us today with exclusively efficient and non-invasive method for visual exploring of human body operation. Another important advantages of the technology deal with relative freedom of experimental methodological approaches. The methodology of experiments enables more detailed control over linguistic stimuli and/or phonetic context, inter-speech articulative postures included.

However, it's worth mention that alongside with the MRI there have been elaborated some other technical capacities to study various types of speech articulation activities that are still widely used in phonetic investigation, namely: electropalatography (EPG) – to examine linguapalatal contact, point-movement tracking; x-ray microbeam, magnetometry for dynamic oral information, and ultrasound for examining tongue-surface contours in the mouth and pharynx. However, none of these techniques presents real-time moving images of articulators along the entire length and diameter of the vocal tract, some of them have serious restrictions in their operability (because of health damages), as well as other essential shortcomings, much less any of the methods is capable to reflect purposeful brain activity on-line. For more detailed comparative analysis of various techniques of visualization of human communicative behavior see also [1].

Fortunately, recent developments in MRI technology for imaging the human body have been very rapid and the imaging technique has turned to be uniquely suited to obtain information of overall tongue shape (both in static position and in its dynamics), including the tongue root, uvula and other articulatory organs. In this paper we'll try to sketch not very long, but still very successful and fruitful history of interdisciplinary research in linguistics based on MRI technology, as well as mention main achievements of such research for Humanities in general with the special focus on its linguistic applications. For more concise review of MRI-based research applications see also [2].

The main areas of MRI employment in linguistic research and in applied research in Humanities in general, nowadays are:

- Research in speech perception;
- Research in speech production;
- Research for applied linguistics – primarily for educational applications (language learning and language teaching),
- Research for computer-based speech processing engineering applications (Speech synthesis and Speech recognition);
- Research for needs of health-impaired therapy and rehabilitation
- Research for various areas in Social sciences (demography, anthropology, etc.).

In the current paper we'll trace out only general outline of the most developed applications of MRI in the modern linguistic science.

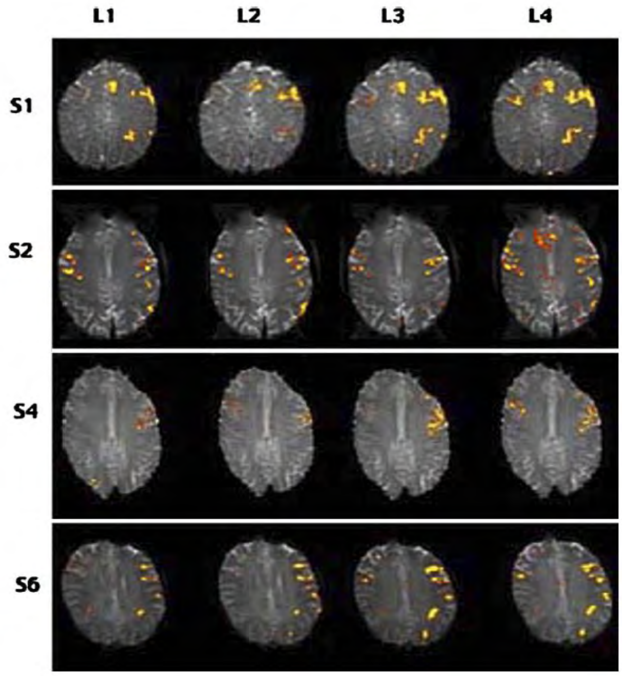
MRI in speech perception

It's obvious today that exploring speech perception and production – more generally, speech signal processing, speech understanding and speech planning procedures, as well as mental and motor speech production processes, strongly needs core MRI capacities that are unique to the technology in question. Therefore, MRI is widely used today in monitoring on-line brain excitation processes during encoding and decoding speech signal, during performing various intellectual verbal and non-verbal tasks. However, it is worth saying that most of the preliminary results of brain speech activities' observation obtained with the use of functional magnetic resonance imaging (fMRI) techniques are not very convincing from the linguistic point of view, though very often they might look quite sensational. These results are in general rather ambiguous, drastically lack robustness, experimental methods are equivocal, therefore many results could have had multiple interpretations that were not verifiable. However, there are still good experimental works in this area as well. One example of the precise trustworthy results of the original investigation of the brain activity worth mention is presented on *figure 1*. The MR images on the figure show activation areas (in comparison to rest) in the brain of 4 quadri-lingual subjects doing a language task in four different languages (L1–L4; subjects S1, S2, S4, and S6) ranked according to the practical acquaintance with the language – from L1 (the best linguistic capacity) to L4 (the worst), shown on the same slice, where representative slices were chosen for the different subjects. Activation is displayed in colors, overlaid onto the EPI images. One could see that all languages tasks activate similar brain areas, however, there is a subtle increase in the amount of activation – namely, the increase in color marked activation from L1 to L4 [3].

MRI-research of speech production processes

However deserving may (and will) be the MRI-based human brain research, the main trend in MRI-based investigation of speech production mechanisms initially was and is still focused nowadays upon thorough examination of speech articulation processes. Magnetic resonance imaging is widely served as a valuable tool both for studying static articulatory postures and dynamic articulatory machinery in every phase of human speech activity. MRI has turned to become a very powerful tool for obtaining vocal-tract geometry data, as it does not involve any known radiation risks and enables direct observation of articulation processes on-line. The MR images have good signal-to-noise ratio, are amenable to computerized 2D and 3D modeling, and provide excellent structural differentiation. In addition, the tract (airway) area and volume can be directly calculated upon these data. Currently it's only ultrasound and MRI that have proved to be viable alternative methods for such investigation [4], [5], however, the both methods are very often complementary.

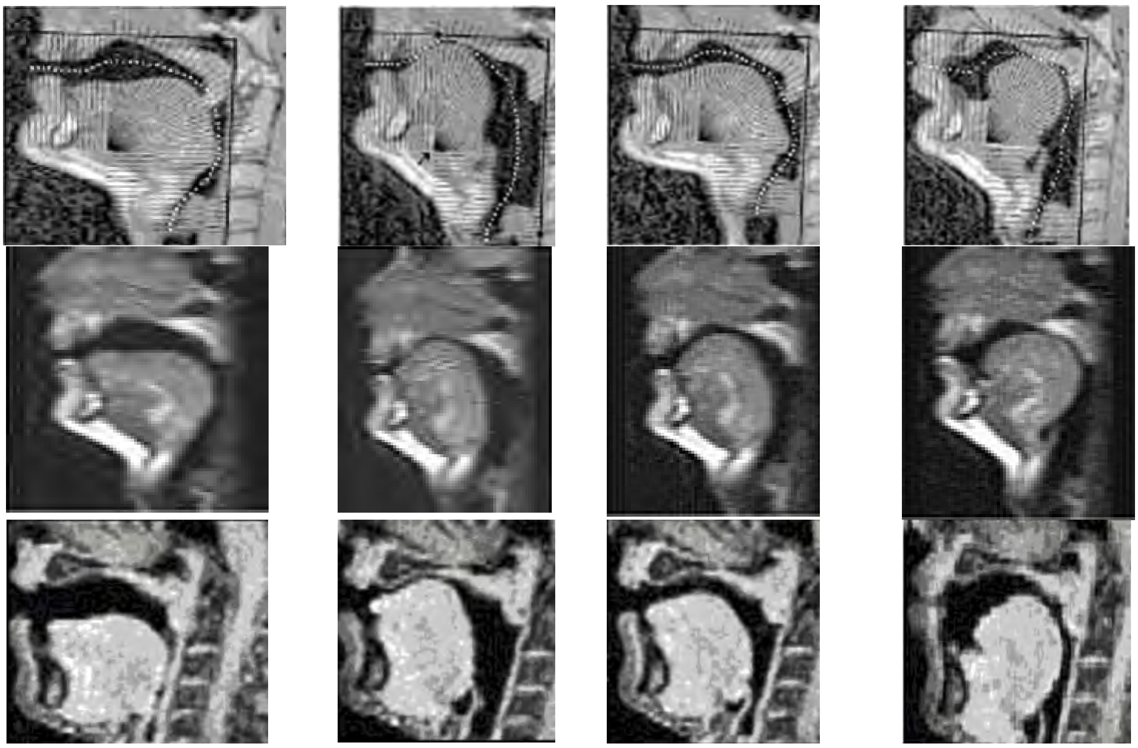
Fig. 1



In the current history of implementation of MRI techniques into linguistic field work one could discern several distinct stages, each stage marked with its proper benchmarks of success in methodology. The history's basic milestones could be defined as follows: a so called initiate ("early stage") phase, mature stage and the advanced one. During the early stage (early 1990s) there were only 2D images, representing selective linguistic data (vowels & spirants in sustained pronunciation); normally there was only single language under investigation, and therefore all research inevitably suffered rather poor statistics [6], [7], [8], [9]. During the so called "mature" stage (after 1995) the quality as well as quantity of the obtained with MRI-technology linguistic data increased substantially: there were built rich databases of 2D images of almost every phase of speech articulation processes (using multiplanar dynamic MRI technique), upon which static models of articulatory movements have been elaborated; there have been several languages under investigation; participation of multiple speakers (up to 35 experimental subjects) became obligatory, enabling thus detailed study of individual articulatory peculiarities; multitudinous (synchronised MRI, audio and video recordings) linguistic data collected [10], [11], [12]. During the current stage (begins in the 21st century) advanced MRI-based research and built thereupon very convincing practical implementations of the previously obtained MRI results were realised; the linguistic data collected consists of: 2D and 3D images taken on-line, articulatory databases in many languages, multiple speakers pronunciation, multitudinous linguistic data, dynamic 2D models of speech articulation, 3D models of continuous speech production processes in dynamics [13], [14], [15].

The first published MRI-based experimental data of articulatory processes' imaging dealt with French and German vowels in tense and sustained articulation that have been "MRI-sed" using special methodology [11], [13]. Similar linguistic data followed soon from experimental work of Japanese and Korean researchers (namely, articulatory profiles of some vowel phonemes of the Japanese and Korean languages accordingly) [16], [17]. Shortly it was the Russian language that enlarged this language pool and launched a new series of contrastive MRI-based articulatory research of the experimental data in several languages' pronunciation practices [18]. On *figure 2* are presented articulatory profiles (sagittal slices) of the cardinal vowels of the Russian, French and German languages. Though according to the theoretical phonetic views these are the same phonemes – same sound types, designated with the same transcription characters – one could see clear differences in resonance volume in speaker's articulatory tract (primarily in the oral cavity) which is defining the perceptible quality of a sound.

Fig. 2. Vowels [a:], [i:], [ɛ:], [u:] (from left to right) in German (upper row), French (middle row) and Russian languages (low row)



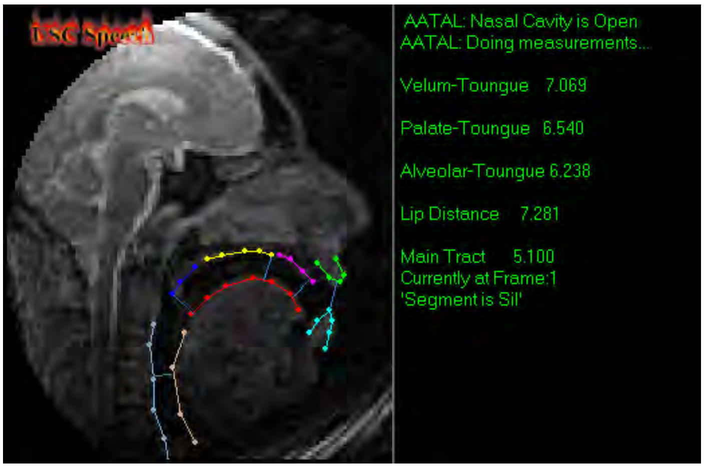
It’s worth mentioning that the Russian language MRI-based experiments substantially differed from the previous international research through original updated methodology of MRI experimental work, and therefore enabled new and rather significant linguistic experimental data [19]. This innovative approach dealt with spreading over various periods of time several series of MR-imaging of the same slice of midsagittal vocal tract area, taken in different time gaps: in one month, with 6-month delay, and in a year. The dataset collected in all the MRI experiments was analyzed to compare the stability of vowel articulation contours within the data obtained from the same speakers in various experimental sessions. One of the most significant results of the investigation was that of significant stability of articulatory motor patterns in articulation behavior of every speaker regardless of the moment of experimental session. Therefore we considered our results as another objective proof of the reality of linguistic concept of phoneme defined by V.A. Bogoroditsky as “psychomotor complex formed in the early childhood via association of contiguity” [20].

Another innovation in the experimental MRI-based linguistic methodology was multiple source information capacities used to identify every single MR-image. The experimental parameters were as follows. All the Russian MRI experimental research was realized in Educational-Research Center of Magnetic Tomography and Spectroscopy of the Moscow State Lomonosov University on a 1.5T MR system (Tomikon S50 «Bruker»). MR scanning was executed on sagittal slice with the slice thickness of 9 mm and to a field of view 200x120 mm. Well known pulse sequence "gradient echo" was used with the following parameters: TR=12 ms, TE=5.5 ms, FA=10 degrees. Under these conditions it was possible to obtain MR images with 2–2,7 frames in a second and with 3 mm in-plane resolution. The receiver coil was a quadrature neck coil. All speaking subjects were lying in supine position, any special mechanism of the head fixation not provided. They were required to repeat experimental Russian language stimuli at their own pace as many times as possible during acquisitions of MR images. Consistently with generally accepted dynamic MRI techniques, we’ve arranged simultaneous audio recordings taken via a microphone LifeVideo(tm) fixed on a receiver’s coil close to the speaker's mouth. As this recording was strongly dominated by the MR scanning machine noise, it was impossible to label reliably and in details the speech sequences, therefore a parallel recording of the starting points of MRI sequences was also previewed. Both recordings were presented as a two-channel oscillogram, which enabled more precise timing of an MR image with a particular phase of phonation, as well as with any phase of pausal period in the future procedures of images’ identification. Later on a video-recording of duplication of the entire experimental session has been taken alongside [21].

Recent advances in methodology of an experiment as well as more powerful technological refinements soon enabled expansion of the research field onto new quantity and quality of experimental material. Thus, very soon followed MRI experiments: focused on different types of speech phonemes other then vowels: at first those consonants enabling sustained pronunciation practices: fricatives [22], rhotics [23] and – last but not least – main Russian stops and several spirants in palatalized and non-palatalized variants [24].

In general one could state that current advances in magnetic resonance imaging technology and experimental methodology applied for investigation of human body have been and still are developing very rapidly. Thus, the most recent improvements in temporal resolution of the MRI system made it possible to examine on-line dynamics of vocal-tract shape changes during fluent speech production−(on-line dynamic MRI). In the year 2004 S. Narayanan reported a novel high speed MRI technique for imaging the moving vocal tract in real time (on-line). The study used spiral k-space acquisitions with a low flip-angle gradient echo pulse sequence on a conventional GE Signa 1.5-T CV/i scanner. This strategy allowed for acquisition rates of 8–9 images per second and reconstruction rates of 20–24 images per second, making veridical movies of speech production possible [25]. The researchers' data obtained through series of MRI experiments shows clear real-time movements of the lips, tongue, and velum. Sample movies and data analysis strategies are presented on the Web-page of SPAN: Speech Production and Articulation kNowledge Group (Univeristy of Southern California), see: http://sail.usc.edu/span/. It is important also to mention that with the elaborated technology segmental durations, positions, and interarticulator timing can all be quantitatively evaluated [26]. An example of such evaluation results is shown on a screen shot presented on *figure 3*.

Fig. 3

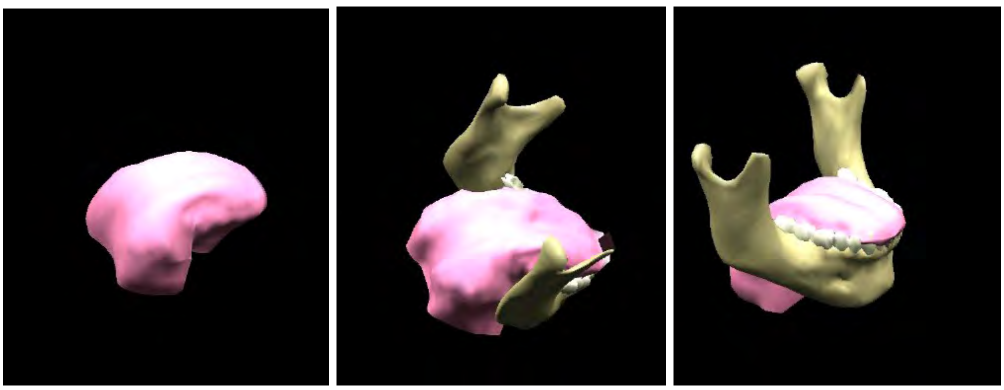


MRI applications in education (language learning)

It has very soon become evident that the ability to acquire real-time images of the speaking vocal tract could provide researchers and computer designers vital data for computational modeling of the speech production process that were not otherwise available [27]. Another progress in the area is achieved nowadays when the use of MRI has gradually expanded from two-dimensional [28] to three-dimensional imaging [29], and from static to dynamic imaging [30]. The celebrated pioneers in the field – researchers from Grenoble (Badin, Bailley, et al.) – thus constructed various artificial models (3D as well) of critical articulators' behavior, primarily fine and detailed tongue transformations during speaking [31]. Screen shots of the Badin's dynamic model of the tongue transformation observed throughout French vocalic articulation processes are presented on *figure 4*.

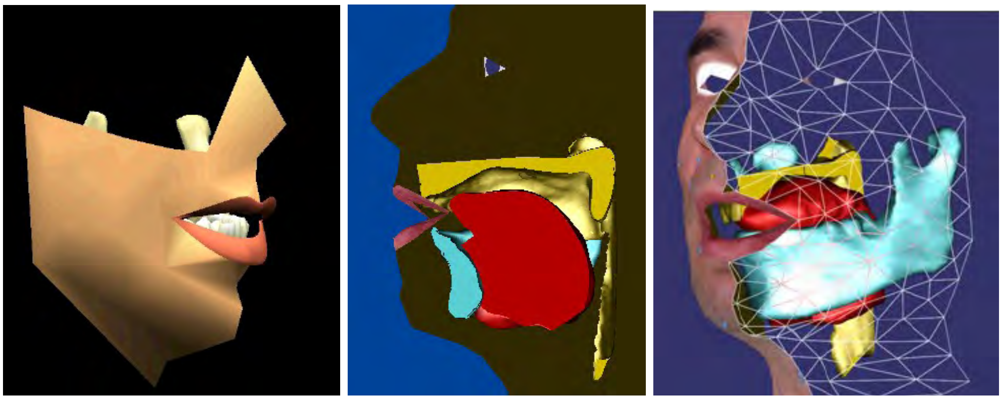
Thus, one could state that recently another ambitious target in MRI research of speech production – that is 3D modeling of the speech articulation in dynamics (articulatory synthesis) has determined one of the main trend in the area. Until now the state of the art in articulatory 3D modeling is still roughly dominated by two main productive schemes. One is using faster and more accurate MRI to measure the vocal tract at different points along the direction of the air stream (e.g. sagittal, coronal, coronal oblique and transversal cuts) while producing speech signals; the measurements' results evolving into the vocal tract's shape reconstruction relying upon this data. This idea has been very soon estimated to be very productive and a series of experimental research conducted in the same strain were not long in coming, resulting thus in a very realistic 3D model of speech articulation processes – a 3D articulatory synthesis called "Virtual Talking Head". Screen shots of the 3D articulatory model of French pronunciation are presented on *figure 5*.

Fig. 4



Currently a series of assessments was under way to test the validity and effectiveness of the "Talking Head" approach. A preliminary evaluation of the contribution of tongue display (exposed in Talking Head avatar) to speech understanding in various degrees of noisy conditions has presented very promising results, thus giving the constructors more stimuli to use the augmented speech capabilities of the virtual talking head for applications in the domains of (1) speech therapy for speech retarded children, (2) perception and production rehabilitation of hearing impaired children, and (3) pronunciation training for second language learners [32].

Fig. 5



Another approach to 3D articulatory models was based upon classical parametric speech synthesis, and is currently developed in the Swedish Royal Institute of Technology (KTH) by Engwall and Wik [33]. The theoretical background of their work was exposed in more details in the dissertations – see [33], [35]. The model consists of vocal and nasal tract walls, lips, teeth and tongue, represented as visually distinct articulators by different colors resembling the ones in a natural human vocal tract.

The internal part of the model includes meshes of the tongue, palate, jaw and the vocal tract walls based on the analysis of three-dimensional MRI data of a reference subject [36]. Using statistical analysis, six articulatory parameters were defined to control the tongue shape. As it was crucial for the proposed application that articulations and articulatory movements were natural and that the timing between the facial and tongue movements was correct, simultaneous measurements of the face (with optical motion tracking of reflective markers) and tongue (with electromagnetic articulography) movements have been used to train the model in a coherent way [37].

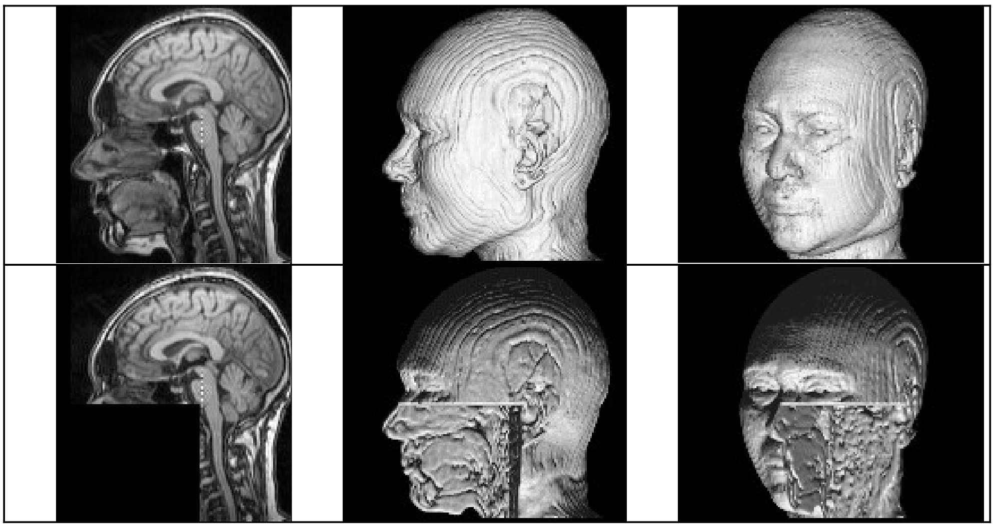
The main hope of the models' authors was that a realistic 3D model of the tongue, made visible in the frame of a synthetic face can be of use in pronunciation training to provide visual feedback to hearing-impaired children. The future ambition of the Swedish research group was to create a tutor that can be engaged in many aspects of language learning from detailed pronunciation to conversational training. Later on such virtual language teacher named Ville was successfully created for teaching and learning Swedish as foreign language. Ville was designed to present language-specific distinctive features in a meaningful contrastive situation, he can detect and give feedback on pronunciation errors, and has many challenging exercises that are used in order to raise the student's awareness of particular perceptual differences between their first and second languages, or to teach new vocabulary.

One of the most challenging capacity of the Swedish approach is that according to the authors' point of view it enables a flexible architecture that allows to create new characters either by adopting a static wireframe model and specifying the required deformation parameters for that model, or by sculpting and reshaping an already parameterized model. Screen shots of the Swedish 3D model of articulation are presented on *figure 6*.

Fig. 6

Thus, one could state that after a certain period of intensive internal development the technology of constructing 3D models of articulatory processes based upon MRI data has evolved and even resulted in some efficient practical applications, at least in several languages (i.a. French and Swedish). The Russian explorers could not stand aside this new trend in MRI-based applications in linguistics and recently a three-dimensional on-line model visualization of the vocal tract as well as of the subject's whole head during speech production was performed based on MRI data obtained from a female speaker producing six cardinal Russian vowels [38]. These images were collected using original method of 3D MRI-scanning where the starting moments of MRI processes enabled co-operative activities from a patient's side via a special remote-control device [39]. A stroboscopic method of data acquisition was used to reconstruct real articulatory processes for each speech stimulus. Data show clear real-time movements of the lips, tongue, underjaw and mandible, as well as velum and facial surfaces. Thus collected animated data could be exposed for improved teaching and learning foreign languages' (in our case, the Russian language) technology, as well as for speech synthesis based on a physiologically relevant articulatory model. Sample screen shots of the model and data analysis strategies are presented on *figure 7*.

Fig. 7



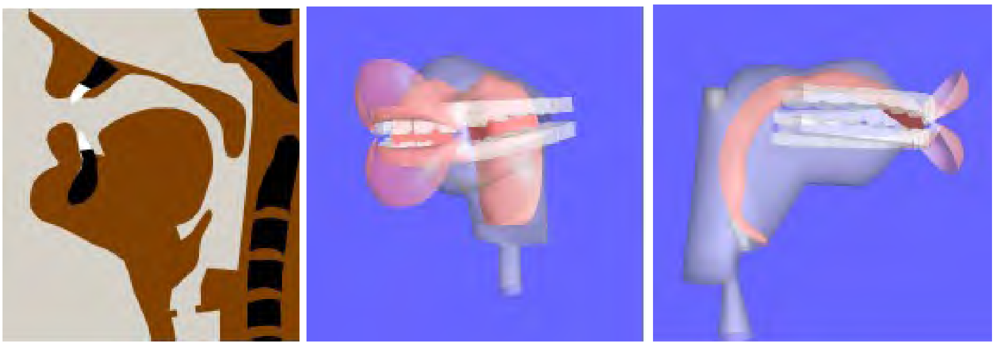
MRI for Rehabilitation & Therapy

Success in modeling articulation processes based on MRI data enabled multiple assessments of efficacy of speech reconstruction models in various fields of their application. Thus, a group of German researchers and clinicians at the University of Aachen with Prof. B.Kröger as a group leader has come a long way in using the original dynamic MRI-based articulatory model for rehabilitation and therapy support [40]. The German 'talking head' – 2D and 3D articulatory model gave very encouraging results in therapy of speech disorders even with young children [41]. Sample screen shots of the model are presented on *figure 8*.

Conclusion

The advances in interdisciplinary use of the MRI technology have proven today its validity and potency in investigation of various aspects of human communication and human cognitive behaviors. Further progress in technology and methodology of experimental work in the field is expected today to be going at a fast pace. We strongly believe that granted to new interdisciplinary approach the prospects for linguistic science, as well as for its multiple various applications look very promising.

Fig. 8



References

[1] *Engwall O.* Combining MRI, EMA & EPG in a threedimensional tongue model // Speech Communication. 2003. Vol. 41/2–3. P. 303–329.

[2] *Narayanan S., Nayak K., Lee S., Sethy A., Byrd D.* An approach to real-time magnetic resonance imaging for speech production // J. Acoust. Soc. Am. 2004. №115(4). P. 1771–1776.

[3] *Briellmann R.S., Saling M.M., Connell A.B., Waites A.B., Abbott D.F. and Jackson G.D.* A high-field functional MRI study of quadri-lingual subjects // Brain and Language. 2004. №89. P. 531–542.

[4] *Stone M.* A three-dimensional model of tongue movement based on ultrasound and x-ray microbeam data // J. Acoust. Soc. Am. 1990. №87. P. 2207–2217.

[5] *Wilson I.* Articulatory settings of French and English monolingual and bilingual speakers. Ph.D. Thesis, Vancouver, University of British Columbia, 2006.

[6] *Baer T., Gore J., Gracco C. and Nye R.* Analysis of vocal tract shape and dimensions using magnetic resonance imaging: Vowels // J. Acoust. Soc. Am. 1991. №90. P. 799–828.

[7] *Narayanan S., Alwan A. and Haker K.* An articulatory study of fricative consonants using magnetic resonance imaging // J. Acoust. Soc. Am. 1995. №98. P. 1325–1347.

[8] *Foldvik A., Kristainsen U. and Kvaerness J.* A time-evolving three-dimensional vocal tract model by means of MRI // Proceedings of Eurospeech'93, Berlin, Germany. 1993. P. 557–560.

[9] *Tiede M.* (1996). An MRI-based study of pharyngeal volume contrasts in Akan and English // J. of Phonetics. 1996. №24. P. 399–421.

[10] *Shadle C.H., Mohammad M., Carter J. and Jackson P.J.B.* Dynamic magnetic resonance imaging: New tools for speech research // Proceedings of the 14th Int. Cong. Phon. Sci. 1999. P. 623–626.

[11] *Hoole P.* On the lingual organization of the German vowel system // J. Acoust. Soc. Am. 1999. №106(2). P. 1020–1032.

[12] *Narayanan S., Byrd D. and Kaun A.* Geometry, kinematics, and acoustics of Tamil liquid consonants // J. Acoust. Soc. Am. 1999. №106. P. 1993–2007.

[13] *Demolin D., Metens T., Soquet A.* Real time MRI and articulatory coordinations in vowels // Proceedings of the 5th Seminar on Speech Production: Models and Data & CREST Workshop on Models of Speech Production: Motor Planning and Articulatory Modelling. – Kloster Seeon. 2000. P. 93–96.

[14] *Hoole P., Wismüller A., Leinsinger G., Kroos C., Geumann A. & Inoue M.* Analysis of tongue configuration in multi-speaker, multi-volume MRI data // Proceedings of the 5th Seminar on Speech Production: Models and Data & CREST Workshop on Models of Speech Production: Motor Planning and Articulatory Modelling. – Kloster Seeon, 2000. P. 157–160.

[15] *Kröger B.J., Hoole P., Sader R., Geng C., Pompino-Marschall B., Neuschaefer-Rube C.* MRT-Sequenzen als Datenbasis eines visuellen Artikulationsmodells // HNO. 2004. Vol. 52. №9. P. 837–843.

[16] *Yang Byunggon*. Measurement and synthesis of the vocal tract of Korean monophthongs by MRI // Proceedings of the XIVth International Congress of Phonetic Sciences (ICPhS 99). 1999. P. 2005–2008.

[17] *Yang C.S. and Kasuya H.* Speaker individualities of vocal tract shapes of Japanese vowels measured by magnetic resonance images // Procedings International Congress of Speech and Language Processing'96. 1996. P. 949–952.

[18] *Kedrova G., Anisimov N., Zaharov L., Pirogov Ju.* Contrastive study of the MRI representation of Russian vowel articulation (against French, German and Korean analogues) // Proceedings of the 33rd International Acoustical Conference. High Tatras. Slovakia. 2006. P. 105–108.

[19] *Kedrova G., Anisimov N., Zaharov L., Pirogov Yu.* Patrons articulatoires lors des pauses anticipatoires en russe: une investigations IRM // La Coarticulation: Des indices à la Représentation. L'Harmattan. Paris. 2011.

[20] *Bogoroditsky V.* Ocherki po jazykovedeniju i russkomu jazyku, Moscow: URSS, 2004.

[21] *Kedrova G., Zakharov L., Anisimov N., Pirogov Yu.* Novyje podkhody v issle-dovanii bazovyh artikuljacij russkogo vokalizma // Linguisticheskaja polyphonija. Sbornik statej. M.: Izdatel'stvo 'Jazyki skavjanskih kul'tur', 2007. P. 770–781.

[22] *Engwall O. and Badin P.* An MRI study of Swedish fricatives: coarticulatory effects // Proc 5th Speech Prod. Seminar. 2000. P. 297–300.

[23] *Espy-Wilson C.Y., Boyce S.E., Jackson M.T.T., Narayanan S. and Alwan A.* Acoustic modeling of the American English (r) // J. Acoust. Soc. Am. 2000. Vol. 108, №1. P. 343–356.

[24] *Kedrova G., Zaharov L., Anisimov N., Pirogov Yu.* Magnetic Resonance investigation of palatalized stop consonants and spirants in Russian // Proceedings of Int. Congr. Acoustics'08 Paris. 2008. P. 2345–2350.

[25] *Narayanan S., Nayak K., Lee, S., Sethy S., Byrd D.* (2004). An approach to real-time magnetic resonance imaging for speech production // J. Acoust. Soc. Am. 2004. Vol. 115, №4. P. 1771–1776.

[26] *Proctor, M., Bone, D., Katsamanis A., & Narayanan S.* Rapid Semi-automatic Segmentation of Real-time Magnetic Resonance Images for Parametric Vocal Tract Analysis // Proceedings of InterSpeech'2010 Chiba, Japan. 2010. P. 1576-1579.

[27] *Bailly G., Bérar M., Elisei F., Odisio M.* Audiovisual Speech Synthesis // International Journal of Speech Technology. 2003. Vol. 6. №4. P. 331–346.

[28] *Stone M., Davis E., Douglas A., NessAiver M., Gullapalli R., Levine W. & Lundberg A.* Modeling the motion of the internal tongue from Tagged Cine-MRI images // J. Acoust. Soc. Amer. 2001. №109. P. 2974–2982.

[29] *Badin P., Bailly G., Revéret L., Baciu M., Segebarth C., Savariaux C.* Three-dimensional linear articulatory modeling of tongue, lips and face, based on MRI and video images // J. of Phonetics. 2002. Vol. 30. №3. P. 533–553.

[30] *Engwall O.* Are statical MRI data representative of dynamic speech? Results from a comparative study using MRI, EMA and EPG // Proc. of ICSLP-2000, 2000. Vol. I. P. 17–20.

[31] *Badin P. and Serrurier A.* Three-dimensional linear modeling of tongue: articulatory data and models // 7th International Seminar on Speech Production (7th ISSP). Ubatuba, Brasil. Center for Research on Speech, Acoustics, Language and Music. 2006. P. 395–402.

[32] *Tarabalka Y., Badin P., Elisei F. and Bailly G.* Can you "read tongue movements"? Evaluation of the contribution of tongue display to speech understanding // Proc. of ASSISTH'2007. Toulouse, France. 2007. P. 187–193.

[33] *Engwall O., Wik P., Beskow J., Granström G.* Design strategies for a virtual language tutor // Proc of ICSLP-2004. Jeju Island, Korea. 2004. Vol. III. P. 1693–1696.

[34] *Olov Engwall*. Studies in Intraoral Speech Synthesis. Doctoral Dissertation. Royal Institute of Technology. Stockholm, 2002.

[35] *Wik P.* The Virtual Language Teacher: Models and applications for language learning using embodied conversational agents. Doctoral dissertation. KTH School of Computer Science and Communication. 2011.

[36] *Hjalmarsson A., Wik P. & Brusk J.* Dealing with DEAL: a dialogue system for conversation training // Proceedings of SigDial.

[37] *Beskow J., Engwall O. and Granström B.* Resynthesis of facial and intraoral motion from simultaneous measurements // Proc of the 15th ICPhS. Barcelona, Spain. 2003. P. 431–434.

[38] *Kedrova G., Anisimov N., Pirogov Yu.* On-line visualization of speech organs using MRI: a 3D approach to speech articulation modeling // Proc. Int. conf. CATE-2008. Crete, Greece. 2008.

[39] *Anisimov N., Kedrova G., Pirogov Yu.* Magnitno-rezonansnoje skanirovanije, upravljajemoje pacientom // Nauchnaja sessija MIFI-2008. 2008. Vol. 3. P. 124–125.

[40] *Kröger B.J., Graf-Bortscheller V., Lowit A.* Two- and three-dimensional visual articulatory models for pronunciation training and for treatment of speech disorders // Proceedings of Interspeech'2008. Brisbane, Queensland, Australia. 2008. P. 2639–2642.

[41] *Funk J., Montanus S., Kröger B.J.* Therapie von neurogenen und kindlichen Sprechstörungen mit dem Programm SpeechTrainer // Forum Logopädie. 2006. №20(2). P. 6–13.

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