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On the History of Computational Modelling and Simulations in the Phonetic Sciences

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Abstract: This paper presents a study on the history of simulation studies in phonetics. Precursors to modern computational models are identified in early mechanical speaking machines. By way of illustration, the historical development is analysed as documented in the proceedings of the International Congress of Phonetic Sciences from 1932 to 2015.

1 Introduction

State of the art methods of computational modelling and simulations in phonetics and phonology have their roots, a.o., in early work on mechanical *speaking machines*. It is less widely known, that numerical simulations with digital computers also have a relatively long history in the speech sciences. In order to understand the history of the application of computational modelling techniques and simulations in phonetics and phonology, a broader perspective is necessary. The advancements of simulation studies within other scientific fields, such as computational linguistics, artificial intelligence, psychology, cognitive and social science are important. As are those advancements in methodology in speech and natural language processing. Simulations entered the fields of phonetics and phonology from different directions. Phonetics is most closely connected with speech synthesis and artificial speech recognition. Phonology, on the other hand, is closely connected with modelling in (computational) linguistics.

Two kinds of research are often discussed with respect to *methodology* in phonetic sciences: Field work, which observes its subject of study *in situ*, and experimental or laboratory work, which could be said to study language *in vitro*. Both observe language and speech *in vivo*, i.e. on living, speaking humans. This paper is concerned with a different kind of research method that emerged during the past six decades: the study of language and speech by means of computational modelling and simulations, observing the subject of study *in silico*. At the 1995 ICPhS in Stockholm, Roger K. Moore presented a "trigger paper" in which he argues for a new, unified research discipline, "*Computational Phonetics*", which addresses speech production and perception by both humans and machines [1]. He notes that this new phonetic discipline is located at the intersection of various scientific disciplines: "Moreover it is precisely in the area of 'speech technology' [...] that the experimental and descriptive fields of phonetics, linguistics and psychology meet the computational disciplines of artificial intelligence, computer science and engineering" [1, p.68]. Moore points out that the progress in speech technology is primarily not due to the integration of linguistic knowledge but due to the application of rigorous mathematical and statistical methods and the increased available computational power [1, p.69]. Tillmann (at the same 1995 ICPhS) defines *Computational Phonetics* as follows: "[...] theories that take values of some given type and compute new values which are not trivially available in the computed form" [2].

It is not possible to provide a complete overview of the history of computational modelling in speech sciences, including phonetics and phonology. This paper discusses exemplary studies

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and reviews their contributions to the field. This paper may serve as a guide and starting point for further research on individual computational approaches and the development of the simulation methodology as a whole. In this paper I restrict myself to the discussion of the historical origins of computational approaches and computer simulations in phonetics which are not presented systematically in other reviews of the history of phonetics.

1.1 Historiography of phonetics and phonology

Koerner [3] provides a review of the historiography of phonetics. He points out that probably "the most thorough treatment of the history of phonetics to date" is the one provided in the second edition to Zwirner and Zwirner's *Grundfragen der Phonometrie*[1]. They [4] provide a detailed overview of phonetics as a philosophical and scientific treatment of spoken language. As far as methods are concerned, they mention Kempelen (see below). In plenary talks at the 12th ICPhS, Liénard [5] reviews the developments from speaking machines to speech synthesis, and Stevens [6] reviews the influence of Klatt's speech synthesizer on phonetics. A detailed overview of the history of speech synthesis – probably the most detailed one – is provided by Köster [7]. An equally thorough treatment of the history of simulations in phonetics and phonology is still missing. Loakes [8] gives an overview of the history of experimental phonetics. She points out important "tools" in phonetics: the International Phonetic Alphabet (IPA) for transcriptions and software packages like Praat and EMU for acoustic analysis. She notes that "it is really the advent of new technologies enabling phoneticians to answer vastly different types of questions about speech" [8, p.126f].

1.2 Terminology

For the purpose of this historical overview, it is first necessary to define some terminology. A *simulation* is defined here as a research technique or method of analysing a given system based on a model of that system. In this case *model* is intentionally ambiguous, referring to both an abstract, formal model as well as a physical simplified replica of a real world object or an apparatus. A model can be informally defined as a theoretical construct used to "explain something in the world" [9]. A *system* in that sense is any formal or real-world object with an internal structure or a set of connected, interacting elements.

A study employing methods from speech technology may be considered a phonetic simulation if the technology is not the focus but used as a research tool to investigate theories or models of human speech production, perception or processing. Fant [10, p.13], for example, notes: "Instead of speaking about phonetics and speech technology, we could make a distinction between theory and applications [. . .]". According to Fant's proposal, computer simulation studies in phonetics and phonology might thus be characterised as those studies which on the one hand employ computational modelling and methods of speech technology, but which on the other hand are not primarily concerned with applications.

2 Thought experiments and simulations

Far less well documented than the method of speech synthesis is the method of thought experiments as one root of computational simulation approaches. Thomason [11] discusses language acquisition and language change as two areas of linguistics in which the device of thought experiments is used by linguists. These are also two areas in which phonetic and phonological simulations are applied for the same reasons that Thomason [11, p.251] states: these areas are

[1] References in this present paper are made to the third, expanded edition, titled *Grundfragen der phonometrischen Linguistik* [4].

"hard to study by direct experimentation". Ohala [12] presents a thought experiment on the evolution of the primitive nature of the segment in phonology. He points out that a computational implementation "was not successful due to the enormity of the computations required and the need to define more carefully the concept of 'segmentality', the expected outcome". Note, however, that a "simple" computational simulation of a hypothetical vowel inventory is employed by Ohala [12] to demonstrate one aspect of his argument.

The ultimate *result* of a simulation is usually a hypothesis [13, p.599]. This is different from the *solution* which is calculated with a computational simulation, i.e. the solution of the underlying mathematical problem. One characteristic feature of computer simulations is that the model and the target system "are made of the same stuff" [13].

3 Rise of the Speaking machines

The artificial creation of speech sounds can be traced back to myths and anecdotal reports about speaking statues from ancient Egypt to the legendary talking head of Albertus Magnus in the 13th century. For the history of simulations in the phonetic sciences are such *speaking machines* of interest which were created out of scientific curiosity. Two traditions can be distinguished: the constructors of such machines tried to simulate the process of articulation and incorporated the available anatomical knowledge of their time. Alternatively, the machines were created with a primary interest in speech sounds without the intention to replicate human articulation.

The early mechanical speaking machines are closely related to musical instruments. The analogy of speech production with aerophones "makes sense from an articulatory point of view", as Fagyal [14] remarks: both produce sound by a (constricted) stream of air. She points out: "[. . .] 17th century inventors' knowledge about the mechanical reproduction of sounds had to come from musical instruments, because grammar books could not be of much use in this respect" [14]. Brackhane [15] points out the close relation between early mechanical speech synthesis and pipe organs (especially the *vox humana*). He describes how the *vox humana* has been idealised as a (supposedly) most natural imitation of the human voice and how this misconception probably lead to the prevailing approach of using is as a voice source in speech synthesis. The idea of a connection between organ-building and mechanical speech synthesis survived until the 20th century [15]. At the first ICPhS, for example, Paget [16] presented mechanical speech synthesis using an organ reed. He uses an organ reed to demonstrate that speech production involves two mechanisms: phonation and articulation. This is an example of a simulation which is used to test a hypothesis.

Historical sources suggest that working speaking machines may have been constructed even earlier than the 18th century [14, 7]. In the 1667 edition of *La Science Universelle*, a textbook on modern science by Charles Sorel, sieur de Souvigny, a hypothetical "speaking machine" is described as a musical instrument with pipes and a keyboard. Another source is Marin Mersenne's work *Harmonie Universelle, contenant la théorie et la pratique de la Musique* (1636) where he also wrote on speaking machines and reported on constructing an instrument to produce vowels. The sources of Sorel's "description of a semi-automatic, multilingual speaking machine modelled after a hydraulic organ, with the potential of using unlimited vocabulary" are traced to 17th century writings on science and mechanics. This suggests that the first attempts at constructing speaking machines were in fact made one century earlier than the documented constructions of the first speaking machines [14].

The beginning of scientific work on mechanical speech synthesis, however, can be identified with the seminal speaking machines by Kratzenstein, Abbé Mical and von Kempelen in the 18th century [17, 18, 19]. While the speaking machines by Kratzenstein or von Kempelen are widely recognised as early achievements in mechanical speech synthesis, the machines constructed by Abbé Mical are not generally known (as well as Mical himself).

By the end of the 18th century, mechanical speech synthesis has been introduced as a research method in the phonetic sciences, which has been further developed until early 20th century [7]. Today, mechanical models of the human vocal tract can still be found, for example, as teaching aids [cf. 20].

4 Systematic literature review of ICPhS proceedings

In this section I present the results of a systematic literature of ICPhS proceedings.

4.1 Quantitative Analysis

I adopt the following working definition of 'simulation study' and search criteria to conduct this literature review: A computer simulation in phonetics and phonology is a research method which involves one of the following:

- artificial speech production (synthesis)
- artificial speech recognition (ASR)
- interacting agents exchanging messages adhering to a given grammar
- formal languages in a dynamic system with external influence (e.g. noise)

A study employing methods from speech technology may be considered a phonetic simulation if

- the technology is not the focus but used as a research tool to investigate theories or models of human speech production, perception or processing

Does the use of synthetic speech stimuli constitute a phonetic simulation study? I leave this question open for discussion. [21], for example, investigate the perception of voice quality variations with synthesized speech samples. [22] present a method to synthesize pathological voice qualities and evaluate synthesized samples through perception tests. I omit papers on text-to-speech synthesis or automatic speech recognition which primarily focus on the technology. A rule of thumb could be this one: if both the *method* applied in a reported study as well as its *topic* are "speech synthesis", then it is probably a paper on speech technology and not a proper phonetic simulation study. As the proceedings of some congresses were not available electronically at the time of conducting this review, they have been reviewed in print. A complete search through the papers for relevant key-words was not possible due to time constraints. The total number of studies incorporating some form of simulations thus has to be seen as a conservative estimate.

4.2 Content Analysis

As a first approach (or, rather, as a methodological exercise) towards a qualitative analysis, the full texts of the relevant papers from the ICPhS proceedings can be analysed with methods from information retrieval and natural language processing. The analysis is restricted to papers identified as *relevant* for the history of computational modelling and simulations in phonetics as described in the previous section. As a further restriction, only papers written in English are included in the content analysis. All calculations have been performed in R using the *NLP*, *tidyverse* and *wordcloud* packages [23, 24, 25, 26]. Relevant papers from proceedings available

Table 1. Total number of contributions for selected ICPhS and the (estimated) number of contributions involving simulations ("sim."). Last two columns indicate the source (printed volumes or PDFs) and number of papers analysed (section 4.2). "NA" indicates missing data.

	congress	year	contributions			proceedings	analysed
			total	sim.	%		
1	Amsterdam	1932	62	1	1.61%	1 vol. print	0
2	London	1935	89	0	0.00%	1 vol. print	0
3	Ghent	1938	87	0	0.00%	1 vol. print	0
4	Helsinki	1961	102	6	5.88%	1 vol. print	4
5	Münster	1964	146	5	3.42%	1 vol. print	5
6	Prague	1967	238	1	0.42%	1 vol. print	1
7	Montréal	1971	162	6	3.70%	1 vol. print	3
8	Leeds	1975	NA	NA	NA	NA	0
9	Copenhagen	1979	250	9	3.60%	3 vol. print	2
10	Utrecht	1983	122	11	9.02%	1 vol. print	3
11	Tallin	1987	650	13	2.00%	5/6 vol. print	13
12	Aix-en-Provence	1991	562	25	4.45%	5 vol. print	25
13	Stockholm	1995	860	52	6.05%	4 vol. print	51
14	San Francisco	1999	642	24	3.74%	full PDF	24
15	Barcelona	2003	859	45	5.24%	full PDF	45
16	Saarbrücken	2007	533	31	5.82%	full PDF	31
17	Hong Kong	2011	579	15	2.59%	full PDF	15
18	Glasgow	2015	774	16	2.07%	full PDF	16

in print have been scanned and the text has been extracted automatically using OCR with some manual corrections.

In order to obtain a list of the most *specific* words for each year, the well-known *tf-idf* vector-space measure for document similarity [27] is used. This measure captures how central a specific word is to a document in comparison to other documents. It assigns a high score for terms which are frequent within one document (*term-frequency, tf*) but do not occur in many other documents (*inverse document frequency, idf*). For this analysis, all simulation-related papers from one congress are treated as a single "document" for which *tf-idf* scores are calculated. The tokens have been converted to all lower case.

4.3 Results

Table 1 shows an overview of the number of related contributions taken from ICPhS proceedings [28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43]. The numbers from this quantitative analysis show that there is an increasing number of simulation studies. However, the relative proportion of studies including simulations is relatively low. Across all proceedings, 21 contributions contain the keyword "simulation" in their title and 73 in their abstract. 240 contributions refer to some form of "model" in their titles and 513 in their abstract. The adjusted number of contributions presenting studies which applied the method of computational modelling and simulations as defined in this present paper is given in column "sim." of Table 1.

Differences arise from the problem that not all simulations are computational and that not all modelling represents a simulation, as discussed above (in particular, the increased application of statistical models may be responsible for these numbers).

Table 2 shows an overview of the 20 most characteristic terms for each congress (in terms of a high *tf-idf* score). The list still contains some obvious recognition errors from the scanned documents or noise from formulas or tables which have not been filtered out from the text. The studies of 1961–1967 seem to be concerned with physiology, voice and equipment. In 1971 the term “neanderthal” shows up [44]. The terms become thematically more diverse.

5 Discussion

The view appears to be spreading among phoneticians and phonologists that a formal model necessarily needs to be implemented. Johnson [45], for example, comments on one of his earlier models and points out the fact that “it wasn’t an implemented model” which he sees as “one key problem”. Only a computational implementation allows for a rigorous investigation of a model and its underlying theory. As Henke [46] pointed out almost half a century earlier: “[a model] must be ‘implemented’ so that its behaviour or ‘outputs’ for given inputs can be observed and compared with the real system. An unimplemented model cannot be so tested and thus seems quite empty of purpose.” The question, whether computer simulations are a new kind of science or if they represent yet another kind of experimental research method is also discussed in the philosophy of science [cf. 47]. There, [13, p.595f] propose to see computer simulations within the continuity of the philosophy of science, instead of postulating something completely new. Accordingly, the recent rapid increase in computer simulation studies in phonetics and phonology is better appreciated as a continuation of a long tradition in our fields of research. While [13] argue that computer simulations are not something entirely new in the philosophy of science and stress their connection to other scientific approaches, [47] emphasizes their epistemic power and their role as explanatory devices.

6 Conclusions

A historic review of the literature on speech sciences shows that precursors to modern day computational models can be identified in mechanical and electronic “simulations” of human speech production. It can also be argued that simulations, as implementations of formal models, are also rooted in thought experiments.

A first attempt at a systematic literature review was presented. It shows that after hiatus in the series of the ICPhS, computational simulation studies had a constant albeit low share in the contributions to the proceedings. Note that this low percentage of simulation studies found in the ICPhS proceedings does not necessarily reflect their impact in the field. The increase in the total number of simulation studies is certainly related to the fact that computers became ever more powerful, smaller and cheaper as compared to previous decades.

A propose qualitative analysis presented here gives an impression of different thematic focuses over the years. The automatic analysis, however, suffers from missing digitized full texts of the early congresses.

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Table 2. Highest scoring terms from simulation-related ICPhS papers.

year	*top 20 TF-IDF terms*
1961	diaphragm, eddies, inspiratory, cords, svend, mucosa, rubber, stroboscopic, cushion, pieces, ring, travelling, membranes, ove, reed, poles, painted, synthesizers, kc, belt
1964	cps, instrumental, cooper, instrumentation, caricature, ibm, manipulator, tomographic, wendahl, helsinki, truby, analyzer, cuts, electrodes, recorders, tape, analog, glottograms, keen, overpressure
1967	creak, nasalised, velarised, whispery, falsetto, blew, harshness, harsh, cis, wind, optional, museular, supralaryngeal, voiee, settings, abererombie, analysable, aooustic, approaeh, artifioial
1971	neanderthal, supra-laryngeal, lieberman, fossil, crelin, linguist, lafon, steinheim, man, nonhuman, paddock, scanian, newborn, generative, neutralization, jakobson, ls, halle, supralaryngeal, n-ary
1979	prog, technol, mosaic, gunnar, wakita, totallength, 2m, 1975a, painting, autonomous, discipline, 1975b, ambiguities, dosage, ekx, hisashi, bandwidths, prof, lpc, infiuence
1983	singing, maccurtain, broecke, fo, deposits, dobzhansky, fink, termites, hirano, folds, pillars, prigogine, skewing, vocabulary, titze, biology, genetic, flow, ug, 1982b
1987	d-type, auditory, resolutions, canal, soundtype, soundtypes, square-law, vsts, karjalainen, distortion, bark, f-space, l-type, x5, icassp-84, alternatives, schröder, v-type, x4, chords
1991	syntagma, kempelen, spu, demisyllable, pec, strands, nn, reed, sonorant, assibilation, controller, faber, phonotactical, voder, ms, adduction, klatt, secondary, rhythmic, jaw
1995	nodules, prototypes, stylization, plant, leak, equilibrium, sf, nodule, flmp, jaw, mpg, aobo, hoarse, articulator, aabb, facilitation, mns, perplexity, motor, f0
1999	pα, α, jitter, upsid, δz, ihc, arx, classi, meddis, 2p, ö, ø, allr, alr, hwr, mri, apex, vot, acceptability, workspace
2003	different, pauses, first, gdd, plp5, f0, agent, dbs, uvfp, z0, clash, hz, hlsyn, facial, imitation, aic, o2, robot, frication, gimel
2007	clo, wd, nrw, infrequent, growth, rel, normalised, exemplar, lenition, intsint, momel, v-to-v, agent, closed-loop, romanian, rp, praat, episodic, acuity, priming
2011	cvs, l2, sonority, l1, f0, mandarin, cci, clicks, qta, chinese, dopamine, env, f2“, ema, ipp, ssm, rmse, dutch, bwa, tone
2015	diana, eː, isi, deficit, aos, f0, aː, ooip, pentatrainer2, focus, rts, feedforward, persian, somatosensory, jaw-lowering, perioral, sas, ms, intercept, apraxia