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Od glasbenih slovnic h kogniciji glasbe v osemdesetih in devetdesetih letih 20. stoletja: viški zgodovine računalniško podprte analize glasbe

From Musical Grammars to Music Cognition in the 1980s and 1990s: Highlights of the History of Computer-Assisted Music Analysis

Ključne besede: računalniško podprta analiza glasbe, kognicija glasbe, psihologija glasbe, glasbene slovnice

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IZVLEČEK

Med tem, ko so se pristopi, ki so že bili postali zgodovinsko ključni - računalniško podprti analitični pristopi temelječi na statistiki in informacijski teoriji - razvijali naprej, je vrsta raziskovalnih projektov v 1980ih želela razviti nove metode računalniško podprte analize glasbe. Nekateri projekti so odkrili nove možnosti uporabe računalnika za simuliranje človeške kognicije in percepcije, opirajoč se na kognitivno muzikologijo in umetno inteligenco - področja, ki sta jih odkrivali tehnični napredek in razvoj računalniških programov. V 1990. so se začele pojavljati revolucionarne metode analize glasbe, zlasti tiste, ki temeljijo na raziskavah umetne inteligence. Nekatere teh metod so se osredotočile bolj na zvok kakor na partituro in so prispevale, da se analiza glasbe ukvarja z vprašanji o zaznavanju glasbe. Pri nekaterih pristopih je prišlo do povezave med analizo glasbe in analizo kognicije.

Prispevek ponuja prerez računalniško podprte analize glasbe v 1980ih in 1990ih, kot se le-ta navezuje na kognicijo glasbe. Razprava obravnava izbor analitičnih pristopov.

ABSTRACT

While approaches that had already established historical precedents - computer-assisted analytical approaches drawing on statistics and information theory - developed further, many research projects conducted during the 1980s aimed at the development of new methods of computer-assisted music analysis. Some projects discovered new possibilities related to using computers to simulate human cognition and perception, drawing on cognitive musicology and Artificial Intelligence, areas that were themselves spurred on by new technical developments and by developments in computer program design. The 1990s ushered in revolutionary methods of music analysis, especially those drawing on Artificial Intelligence research. Some of these approaches started to focus on musical sound, rather than scores. They allowed music analysis to focus on how music is actually perceived. In some approaches, the analysis of music and of music cognition merged.

This article provides an overview of computer-assisted music analysis of the 1980s and 1990s, as it relates to music cognition. Selected approaches are being discussed.

Introduction: Musical Grammars and the 1970s[1']

In the 1970s, the search for a musical grammar was probably the most important development in computer-assisted music analysis. The basis for this search was provided by the insight that specific compositions could be represented in terms of a list of grammatical production rules. One of these forms of representation is the parse tree, which graphically represents the syntactic structure of a composition. One of the first attempts of applying Heinrich Schenker's theory of tonality to computer-assisted analysis of music was made in the 1970s by Michael Kassler (1975a, 1975b, 1977; see also Kassler 1964). He explicated the middleground of Schenker's theory and programmed[2] the decision procedures for formalized languages that constitute this explication (see Kassler 1975b, 7). A LISP-based system for the study of Schenkerian analysis was developed by Robert E. Frankel, Stanley J. Rosenschein, and Stephen W. Smoliar (1976, 1978). Since the programmed procedures were essentially a description of Schenker's hearing of the musical works, this approach was one of the first to model musical perception on a digital computer. Schenker's tonal and transformational hierarchies were represented within the context of a symbol-manipulation system in terms of tree transformations. A data structure was implemented that modeled the process by which the hierarchy was (supposedly) created. To demonstrate their computerized modeling, Frankel, Rosenschein, and Smoliar analyzed parts of Beethoven's "Ode to Joy". They summarized their work as follows: "Although we have not yet reached the axiomatisation stage, our LISP-based system may prove of immediate value to the musicologist and the composer. Computer-aided musicological and compositional projects have a long history. We feel our formalism of Schenker's notions of musical structure could significantly effect future developments of both fields. In almost all documented attempts to use the computer as a tool for stylistic analysis, the data structures employed represented musical information in the form of strings of characters. … The representations fail to capture any hierarchical structure internal to a composition. … We have, in fact, the capabilities for modeling such a growth process in our LISP system as shown above by our analysis. By contrast, those data and control structures which are based entirely on string manipulation are inadequate in this respect. In fact, with a LISP-based model the musicologist may more readily ask questions about 'deep structure' and its transformations which he may use to establish criteria for stylistic analysis." (Frankel, Rosenschein, and Smoliar 1976, 29-30.)

Already in the early 1970s, Otto Laske's search for a grammar of music was an exploration of a "generative theory of music" (Laske 1972, 1973, 1974, 1975, 2004). But Laske's grammar concept was based not on notated music, but on a formal model of empirically acquired musical *activity.* Thus, Laske's studies were early studies in musical cognition. He was interested in formal properties of cognitive tasks that process musical input. "Instead of producing a taxonomic analysis of musical structures, Laske has turned to what is essentially a project in cognitive psychology." (Roads 1979, 52.) Laske's understanding of 'sonology' expressed "the relationship between the syntactic structure of a music and

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its physical representation in so far as this relationship is determined by grammatical rules" (Laske 1975, 31). Laske tried to explicate musical grammars as computer programs in so far as they, more or less, relate to musical activity, such as composing or listening. This provided the basis for a unique analytical approach developed in the early 1980s (Laske 1984; see further below).

The 1970s were a rich decade for computer-assisted music analysis. Existing (statistical and information-theoretical) methods were refined, separate measurements were converted into complex, multi-factor analyses, and, most importantly, the core of computer-assisted, analytical methods was extended by psychological and set theoretical approaches as well as approaches drawing on Schenkerian analysis and generative grammars. With research on musical grammars, especially that of Otto Laske, the foundation for a cognitive musicology was provided.

Computer-Assisted Music Analysis and Music Cognition Research in the 1980s

While approaches that had already established historical precedents - computer-assisted analytical approaches drawing on statistics and information theory - developed further, many research projects conducted during the 1980s aimed at the development of new methods of computer-assisted music analysis. Some projects discovered new possibilities related to using computers to simulate human cognition and perception, drawing on cognitive musicology and Artificial Intelligence, areas that were themselves spurred on by new technical developments and by developments in computer program design.

Reiner Kluge (1987) presented an application of his theory of active (complex) musical systems to the analysis of (Afro-Cuban and Algerian) ostinato rhythms. Using the model of a 'complex system', which includes hierarchic structures, self regulation, accidental effects, etc., the analyses were directed at the statistical evaluation of the rhythms (specifically by calculating correlations) and at the psychological and historical-cultural structures that were involved in the creation of these rhythms.[3] The analysis was also directed at the "inner time organization", i.e. the time that is 'experienced' by the listener. Thus, Kluge's analytical approach could only be carried out by linking the statistical calculations (and their procedures) with interpretative activities of the musicologist. Even though not actually realized with the aid of a computer, Kluge's approach to complex data processing was an important step towards further research in the field of Artificial Intelligence.

Dean Keith Simonton's research was based on William J. Paisley's analytical attempts.[4] Simonton (1980a) combined computer-assisted analyses of two-note transitions within the first 6 notes of 5046 classical themes (by ten well-known composers) with broader,

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Based on communication theory, William J. Paisley (1964) made a fundamental contribution to identifying authorship (and with it, stylistic characteristics) by exploring "minor encoding habits", i.e. details in works of art (which would be, for instance, too insignificant for imitators to copy). (For a general discussion on this topic, especially with regard to text analysis, see also Paisley 1969.) To take an example from a different field, master paintings can be distinguished from imitations by examining details like the shapes of fingernails. Similarly, Paisley tried to show that there are indeed significant minor encoding habits in music. - On the limitation of Paisley's approach, see, for example, Schüler 2006a.

more encompassing, analyses of psychological and socio-cultural factors. His goal was to find musical characteristics that make a musical theme 'famous.' 'Thematic fame' was defined, on the one hand, with regard to the frequency of performances, recordings, and citations (ibid., 210). On the other hand, "melodic originality was operationalized as the sum of the rarity scores for each of the theme's 5 transitions" (ibid., 211). Chromaticism and dissonant intervals played an important role in the statistical calculations. But Simonton neither calculated note transitions of higher orders (beyond two-note transitions), nor did he calculate transitions related to duration or rhythm. Even though some of his results[5] are still valid, most of them are not, especially those dealing with the empirical determination of 'thematic fame' and with the correlation of 'creativity' and Simonton's calculations of 'melodic originality' (interpreted as 'novelty'). Recent research on musical creativity[6] does not support Simonton's understanding of 'melodic originality'. Nevertheless, within a history of computer-assisted music analysis, the attempt of combining psychological and sociocultural factors and statistical analyses was an important step.

Later on, Simonton (1980b, 1983) refined his approach usimg 15,618 musical themes by 479 classical composers, and he considered further analytical variables, e.g. "Zeitgeist melodic originality", which is "the degree to which the structure of a given theme departs from contemporaneously composed themes" (Simonton 1980b, 974). With this approach, he gained more detailed and more accurate results.[7] In 1984, Simonton presented two-note transition tables from his former studies as well as three-note transitions and more thorough interpretations of them to support his (earlier) results. Finally, one of the goals of Simonton's studies was to stimulate further research in music psychology and aesthetics. However, only a few of further research projects in music psychology and aesthetics followed Simonton's methodology, and those who did produced insignificant results.

The development of new models of syntactic structures in linguistics suggested new ways to describe syntactic structures in musical compositions. Specifically the application of concepts derived from Noam Chomsky's generative-transformational grammar[8] to the analysis of music was of special importance to several developments in music theory. A generative grammar is based on a theory that could specify a *structural description* for any (grammatically correct) syntactic structure and the rules for creating variations of it (no matter whether the structure occurs in a sentence or a phrase of music), instead of enumerating which sentences or pieces of music are possible. And just as Chomsky was concerned, while developing his grammar, with the cognitive representation and the perception of language, those who applied Chomsky's grammar to music theory

Simonton's main results were: 1. 'thematic fame' is a positive linear function of melodic originality; 2. melodic originality of themes increases over historical time; 3. melodic originality of a theme increases when composed under stressful circumstances in a composer's life; and 4. melodic originality is a curvilinear inverted backwards-J function of the composer's age. (Simonton 1980a, 213-215.)

See, for instance, Gardner 1993 as well as Feldman, Csikszentmihalyi, and Gardner 1994.

Simonton corrected, for instance, that "thematic fame" was then represented by an inverted-J function of "repertoire melodic originality" (i.e., unusual melody in comparison to the entire repertoire of music listening) and that "thematic fame" was also represented by a J function of "zeitgeist melodic originality" (ibid., 977). Furthermore, the "thematic fame" was a curvilinear inverted-U function of a composer's age (ibid., 979). Simonton stated that "as the thematic richness of a work increases, the fame of any single theme within the work becomes less dependent on the intrinsic properties of melodic originality and becomes more dependent on associations with other themes via the formal structure of the piece" (ibid, 979); this shows also the problem of the definition of "theme" and the differentiation between 'theme' and 'motive'.

[3]   See Chomsky 1965, 1969, and 1972.

also wanted to understand musical cognition. As used in linguistics or music theory, a generative-transformational grammar involves the application of a number of transformational rules and rules for constructing phrase structures to a set of elementary relationships. Since the model was mostly restricted to structures that are hierarchical in nature, structural trees were often used to visualize structural dependencies, and have become a useful concept in various aspects of (computer-assisted) music analysis.

Fred Lerdahl and Ray Jackendoff (1983a, 1983b) developed another model of the analysis of hierarchical structures; they extended the notion of a generative grammar into a notion of "a generative theory of tonal music". Lerdahl and Jackendoff distinguished four structural components of music: 'grouping structure' (hierarchical segmentation into motives, phrases, and sections), 'metrical structure' (hierarchical beat levels), 'time-span reduction' (hierarchy of 'structural importance') and 'prolongational reduction' (hierarchical harmonic and melodic levels). All structural components are described by rules of the following three types: 'well-formedness rules', 'preference rules', and 'transformational rules'. Applying this theory to computer-assisted analysis, Leilo Camilleri (1984) described grammatical structures of the melodies of Schubert's Lieder. Camilleri developed a methodology for analyzing phrases of songs taken from *Die schöne Müllerin, Winterreise,* and *Schwanengesang.* This methodology was based on the following principles:

- "generation of a possible 'initial phrase' of a melody of a Schubert Lied by means of a syntactically structured grammar with rewriting rules, based on previous observation, subjective knowledge, etc.;
- verification of the suitability of the grammar through examination of the corpus;
- adjustment of the grammar by means of the formulation of other rules which permit a correct description and generation of the phrases." (Camilleri 1984, 229.)

A LISP program was entrusted to verify Camilleri's model, which showed that specific rules (transition rules, cadence rules, and ornamentation rules) could indeed be explicated to describe the grammatical structure of music.

Stephen W. Smoliar (1980) applied a different concept of musical grammars to computer-assisted music analysis. Already at the beginning of the 20th century, Heinrich Schenker worked out a specific concept of musical grammar, in which hierarchical subdivisions of the 'Vordergrund' ['foreground'], 'Mittelgrund' [middleground] and 'Hintergrund' ['background'] were analyzed. In Schenker's theory, the surface structure was obtained through the extension of smaller structural units (of the background). The aim of the analytical process was to find an 'Ursatz' [fundamental structure]. Based on this theory, Stephen W. Smoliar discussed the establishment of a system for experiments in computer-assisted Schenkerian analysis. Structural levels were represented through logical combinations of elements (tones, chords). Smoliar's system embodied successful Schenkerian transformations. The program provided analytical tools in the form of macro definitions of constructs and transformations (within different levels). Smoliar's goal was to fill a database of analyses, which can be used for analyzing other compositions.

Other approaches to computer-assisted music analysis in the 1980s were derived from Artificial Intelligence, an interdisciplinary area which uses computer models to examine the intellectual capabilities of humans and the nature of their cognitive activ-

ity. Already in the 1970s, Otto Laske founded a "cognitive musicology" that was directed at musical activities. The goal of Laske's cognitive musicology was an empirically supported theory of musical intelligence (Laske 1977a). The computer is the most important tool in formulating theories of musical actions that are empirically verifiable. As Laske pointed out, musical artifacts should not only be analyzed as pure syntactic structures, but also with regard to the underlying human competence involved in the performance of music. In this case, *competence* is defined as knowledge concerning the structure of the medium in which a communicative act takes place; *performance,* on the other hand, is understood as knowledge concerning the ways in which this competence is utilized in the act of communication (Laske 1975, 1). In making such a distinction, music is conceived as a series of tasks; its cognitive structure and processes need to be analyzed. To develop this methodology, Laske drew on linguistics, psychology, computer science, and Artificial Intelligence, and adopted the premise that the understanding of music requires an understanding both of structures of musical tasks and of musical processes.[9] Thus, for instance, the reading of a score by a conductor, by a musicologist, or by a music analyst are different tasks (performance), although they require a common music-analytical competence.[10]

In 1984, Otto Laske described the set of computer programs he developed, called "KEITH", as a rule-based system generating musical discoveries. A number of distinctions evolved from his work with this system. He began to distinguish between three kinds of musical representations: 'what is heard' ('sonological representation'), 'what is understood' ('music-analytical representation'), and 'what is said' ('linguistic or music-analytical representation'), and saw each as a component of the analytical project. Given that Laske sought to model both the analytical concepts of his test subjects and the problem solving behavior involved in their music-analytical behavior, it is not surprising that, in the realm of computer-assisted analysis, he would be specifically interested in what a computer program had to 'know' to pursue an analysis of a specific composition. Perhaps the most unique aspect of Laske's approach to music analysis was that he developed a theory of analytical processes: He pointed out that a theory of product, the kind of theory formulated by most music theorists, can be, and should be, complemented by a theory of processes. Laske conceived music analysis "as a discovery process that generates new concepts and conceptual linkages between them, in a search based on systematically derived examples." (O. Laske in Schüler 1999, 148.) His theories have much to offer for new efforts in the realm of computer-assisted music analysis.

An approach to musical analysis that draws on Artificial Intelligence (AI) first began to develop in the late 1980s. It is characterized by the use of a programming concept called neural networks. Neural networks are programs with units connected in networks, analogous to the network of neurons in the nervous system. Specifically, neural networks are a class of dynamic computer programs that are used by theorists (including music

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An introduction to (Laske's) cognitive musicology was provided by Nico Schüler (1995a). There, a bibliography of Laske's writings can also be found. See also Balaban, Ebcioglu and Laske 1992, Laske 2004, Schüler 1995, 1997, 1998, 1999, 2006b, and Tabor 1999a, 1999b. For further developments in cognitive musicology see Laaksamo and Louhivuori 1993 and Seifert 1993.

[13] In this sense, musicology itself becomes a task; the understanding of its structure and process is one goal of cognitive musicology. See Schüler 1993, 3-4.

theorists) to analyze some activity by simulating the behavior of the nervous system.[11] It involves the study of how massive numbers of various kinds of elementary units, governed by relatively simple rules, can generate complexity and change within a large, dynamic system. Although the approach was promising, it was not until the 1990s that important contributions to music analysis started to be made.

AI, Cognition, and Computer-Assisted Music Analysis in the 1990s

Continuing a trend that had already started in the 1980s, computer-assisted analytical methods shifted from statistical methods to methods drawn from Artificial Intelligence and cognitive sciences. This shift can be exemplified by several important research projects. John Schaffer (1992, 1994), for instance, proposed and developed a PROLOG-based computer program[12] that enabled the user to define and change analytical criteria while the program was running, i.e. without having to rewrite the program itself. Thus, "the user interacts with the program by repeatedly asserting sets of criteria that the program tests, refines, and feeds back as relevant information to the user - or, if deemed significant, to itself, for further examination. … The power of the system comes not from what it does, but from how it does it. In the best sense, it emulates the human processes of heuristic exploration, but it does it much more quickly, more consistently, and, more importantly, in an interpretative manner. The computer is no longer relegated solely to the role of user-interpreted data generation and manipulation, instead it is empowered with the ability to assess and adjust continuously to new information while continuously interacting with the human analyst." (Schaffer 1992, 147.) Using the concept of nodes and spines, Schaffer formalized a flexible PROLOG data structure for expert systems. Nodes represent all discrete dynamic objects such as notes and rests. All discrete nodes are linked by spines, creating sequentially ordered lists. The advantage of this system is that all analytical structures need to be created only once; editing the event lists is made very easy. The program, then, is able to "use various programmer-defined concepts to begin inferring relationships and refining search strategies without significant user input. … In this sort of exploration, the program begins by examining all combinations of event groupings employing a forward-referencing depth-first search heuristic intrinsic to the *Prolog* environment." (Ibid., 153.) Schaffer used this system to analyze selected atonal music, in a manner related to analysis based on set theory. He used fuzzy logic to include certain degrees of uncertainty. Schaffer found this procedure especially useful with respect to searching for the manifold hierarchies and interrelationships in music. Through inclusion of fuzzy logic, the program "could gain the ability to evaluate and assess musical materials in a manner enhanced by continuous reassessment and adjustment based on the ever-changing vagueness weights of previously observed" phenomena (ibid., 155-156). To exemplify the value of his new analytical procedures, Schaffer analyzed Anton Webern's *Six Bagatelles,* op. 9.

Mark Leman (1991a) gave, for instance, an introduction to artificial neural networks and their applications in musicology.

[12] PROLOG is a programming language for rule-based or logic programming, oriented to action when declared conditions are met. It is based on the first-order predicate calculus of mathematical logic.

Marc Leman (1995a) designed a psycho-acoustical model for "tone center recognition and interpretation", drawing on research in musicology, psychology, computer science, neurophysiology, and philosophy. Leman used his model to analyze perceivable tone centers in music, using musical sound as the program input, thereby avoiding symbol-based paradigms in which music is conceived as a set of symbols (like in a score). Instead, he developed a "subsymbolic" representation of music, that is a representation of the sound. Leman's computer program is strongly grounded in psychoacoustic research and includes, for instance, self-organization and the ability to learn. The main approach is based on "schemas" in that the perception of specific incoming (perceived) images might be actively controlled. His approach allows for the notion of context sensitivity. "The role of an active schema is particularly relevant in cases where previous semantic images are reconsidered in the light of new evidence. Consider a sequence containing the chords IV-V-I. After hearing the first chord, the tone center will point to the tonic that corresponds with degree IV. It is only after hearing the rest of the sequence that the first chord can be interpreted in terms of its subdominant function. The schema should thus control the matching process and adapt the semantic images in view of new evidence." (Leman 1995a, 126.) The output of the computer analyses was compared with 'traditional' analyses by a musicologist. Using what he calls "tone center recognition analysis" and "tone center interpretation analysis", Leman discussed differences between analyzing mere melodic pieces and analyzing predominantly harmonic pieces. While Leman's approach to tone center recognition was less successful in analyzing melodic pieces, his results also suggested that tone center recognition and rhythmic grouping are interrelated.

Similar to Leman's connectionist model, i.e. a model that makes use of brain-style computation,[13] Don L. Scarborough, Ben O. Miller, and Jacqueline A. Jones (1989 [reprinted 1991]) suggested a connectionist model for tonal analysis. Unlike other, similar, approaches to tonal analysis that fail to deal with aspects of human perception of music and that fail to explain musical similarity, the approach of Scarborough et al. included the design of a network for "tonal induction", which simulates the perception of tonal relations and similarity. In their network, the "key node" that is most active controls the mapping of the notes, i.e. the various relationships between the keys. "Singling out one key node and disabling the others can be accomplished by letting the output of key nodes be a non-linear sigmoidal function of the input, and by adding inhibitory connections between key nodes." (Ibid., 58.) Unfortunately, the model described has neither been tested on a large amount of musical data nor has it been compared to a psychological experiment that could demonstrate how well the networks simulate human perception.

Ilya Shmulevich (1997), while carrying out dissertation research on properties and applications of monotone boolean functions and stack filters, designed a computer system to recognize and classify musical patterns. His goal was to create a system that could minimize pitch and rhythm recognition errors, produced when trying to match

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[13] Connectionist systems make use of 'brain-style' computation, i.e. making use of a large number of interconnected processors operating in a strong parallel distributed fashion. Connectionist approaches embody learning, constraint satisfaction, feature abstraction, and intelligent generalization properties. (See especially Todd and Loy 1991.)

a scanned pattern with a corresponding target pattern. To recognize perceptual errors, Shmulevich applied (a modified version of) Carol L. Krumhansl's key-finding algorithm, which provides a most likely tonal context for given musical patterns.[14] Based on this algorithm, the computer calculated a sequence of maximum correlations. The results were then weighted for perceptual and absolute pitch errors. Other parts of the program computed the complexity of rhythm patterns with the goal of weighting possible pitch errors. Shmulevich concluded that a future application of this system could be the computerized search for compositions containing the closest match with a memorized melody (target pattern).

David Cope (1991, 1996) developed the LISP-computer system "Experiments in Musical Intelligence" (EMI), which combines analysis and composition processes. His goal was to write music in a specific musical style. Cope's analyses are based on hierarchical analysis, drawing on Schenkerian analysis and on Chomsky's generative grammar of natural languages. Cope's EMI as well as his "Simple Analytic Recombinancy Algorithm" (SARA) can analyze each component of a composition for its hierarchical musical function, match patterns for "signals" of a certain composer's style, and reassemble the parts sensitively, using techniques drawing on natural language processing (Cope 1996, 28). Part of the analysis process involves a pattern searching algorithm that, in contrast to pattern-searching algorithms by other authors, seek patterns without any preconceived notion of their content. That means, the analyst does not need to know which patterns are supposed to be matched. "EMI employs a limited set of variables called controllers, which affix musical parameters to vague outlines within which patterns are accepted as viably recognizable." (Ibid., 36.) Many compositions generated on the basis of analytical results are proof of Cope's success.

Mira Balaban (1992) described computational procedures that focus on hierarchical relationships in musical activities and on the aspect of time in such activities. The formalisms used in this approach support the following descriptions of music:

- partial descriptions (musical structures and patterns of a composition),
- complete descriptions (fully specified pieces),
- implicit descriptions (some processing is needed to find the denoted structures in a piece), and
- explicit descriptions (explicitly specifies the sound properties).

Balaban's representation allows grouping of musical structures (hierarchies) over time, without implying conclusions about the "grouped object". Balaban's formalism was intended to explore musical *activities* in a standardized form. Analysis is only one of these activities that the system can support. Others are composition and tutoring. However, the *analytical* extension of this system had not been completely realized.

For her dissertation research, Judy Farhart (1991) developed a GCLISP-computer program that could identify keys. It was a knowledge-based (expert) system with rules of musical syntax and syntactic procedures and was written to simulate intelligent behavior, specifically learning processes, as well as interactive and interpretative procedures. The input data (MIDI) were interpreted to identify note names by reiterating possible paths

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[14]   See Krumhansl 1990 and Takeuchi 1994. This key-finding algorithm is based on the observation that tones that are sounded most frequently are, in a specific tonal context, the ones with a high probe of tone ratings. See also Shmulevich 1997, 65.

in a tree structure, applying the knowledge rules of recognizing the tonality in a specific key. Farhart's Artificial Intelligence procedures of key identification had its potential to identify proper note names, matching them with all other notes within a specific key.

At the University of Nijmegen in the Netherlands, Peter Desain and Henkjan Honing launched one of the most extensive research projects that involves research on music cognition and that applies means of Artificial Intelligence.[15] Some of the projects and procedures, developed as part of this broad research project, named "Music, Mind, Machine", are related to computer-assisted music analysis.[16] All of their analytical procedures are part of the LISP-based POCO software package (see, for instance, Honing 1990). Most of the projects within "Music, Mind, Machine" use digital sound as the source of the analyses, aiming at performance practice and related issues, including structures of performed music.

As part of the "Music, Mind, Machine" studies, one project has been dealing with matching performances (in the form of digital sound) with their printed score (see Desain 1998a). Hereby, the timing is of special interest, since expressions in timing (of performed music) can vary by up to multiples of the original (notated) value of notes. The program developed was able to extract patterns of expressive timing and calculate local tempi. The matching editor made use of structural information, taken from the score, and produced better results than already existing 'structure-matcher'.[17] However, more detailed knowledge of the wide variety of musical structures is necessary to make the program more robust and more successful.

Another project of the "Music, Mind, Machine" studies is related to vibrato. The project's goal is to investigate empirically the relationship between vibrato, musical instruments, and global tempo. The digital audio of several commercial recordings of "Le Cygne" by Saint-Saens as well as performances of the same piece with different instruments have been analyzed specifically regarding expressions in vibrato. The knowledge obtained from these analyses was condensed into a formal computational model that can predict the nature of vibrato performed on different instruments in different structural relationships. Furthermore, it can be applied to make synthesizers more 'intelligent' in their implementation of vibrato. (See Desain 1998a; Desain, Honing, Aarts, and Timmers 1998.)

Another project within "Music, Mind, Machine" is directed at the perception and performance of grace notes. Results of analyses suggested that not only tempo but also the structural function of a grace note might influence its duration. From the musicological literature, the research team drew several hypotheses about the structural classification of grace notes and the effect of this classification on their durations. They found that, although grace notes in certain structural categories are consistently played longer than

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[15] This research is based on preceding studies by Peter Desain and Henkjan Honing, published partly in Desain and Honing 1992a. The large-scale project was launched in 1996/97 with several post-doctoral and other positions, which initially were filled by Peter Desain, Henkjan Honing, Rinus Aarts, Hank Heijink, Ilya Shmulevich, Renee Timmers, and Luke Windsor. Some of the personnel changed in later years.

[16] A detailed description of the research projects, many of the published articles, and the software package are available on-line at http://www.nici.kun.nl/mmm/.

[17] Those existing 'structure-matchers' are developed and used in different contexts and for different tasks. Some focus on real-time matching (Dannenberg 1985; Vercoe and Cumming 1988; Vantomme 1995), others on off-line analyses, for which the analysis is more important than the efficiency of the program. Most of the 'structure-matchers' match primarily pitch, sometimes in combination with time information. The "Music, Mind, Machine" matcher matches pitch and time.

grace notes in other categories, the major influence on grace note timing seems to be stylistic. They also found that some grace notes get longer as the tempo decreases, while others retain approximately the same duration. The authors considered this as strong evidence against the notion of relational invariance across different tempi. (Desain 1998a, 8; see also Windsor, Desain, Honing, Aarts, Heijink, and Timmers 1998.)

The quantization of temporal patterns,[18] i.e. their subdivision into small finite increments that are measurable, is another project within the "Music, Mind, Machine" studies. Objects of this project are the actual tone durations in performed music, which deviate considerably from the notated durations. The research shows that those deviations are related to the musical structure. Several elementary models for tempo deviation and for grid-based quantization have been developed. The research is ongoing, like many other projects within "Music, Mind, Machine." (See Desain 1998a; Trilsbeek and Thienen 1999; Cemgil, Desain, and Kappen 1999.)

Another computer program that was used in several research projects is David Huron's Humdrum toolkit (Huron 1993c, 1995, 1999a). It makes use of the *kern* (alphanumerical) music representation. The capabilities of Humdrum's toolkits, a collection of (then) more than 70 interrelated software tools, are broad and range from statistical analysis regarding pitches, tone durations, and intervals to classifications of musical events, melodic search procedures, and harmonic analysis. Several researchers have used Humdrum for specific music analytical tasks. Denis Collins and David Huron, for instance, collaborated in a project on voice-leading in cantus firmus-based canonic compositions. They specifically analyzed the canonic compositional rules of Zarlino, Berardi, and Nanino. The study showed how well described musical practice is in theoretical treatises (Collins and Huron 1999).

Unjung Nam (1998) analyzed pitch distributions in Korean court music. Using Humdrum, Nam found evidence (similar scale intervals, similar phrase-ending tones, and similar tone-duration distributions) that a genre-related tonal hierarchy may exist in traditional Korean court music.

Analyzing 75 fugues by J. S. Bach with the Humdrum toolkit, David Huron and Deborah Fantini (1989) provided music-theoretical evidence for the experimentally observed phenomenon that, in polyphonic music, entries of inner voices are more difficult to perceive than entries of outer voices. The study showed that Bach was allegedly much more reluctant to use inner-voice entries in five-voice textures than in three- or four-voice textures. Huron and Fantini hypothesized that Bach tried to minimize perceptual confusion in compositions with a higher textural density.

A different approach to computer-assisted music analysis was taken at the University of Karlsruhe in Germany in a research project on information structures in music. Scholars there tried to model musical structures with rule-based systems. Stylistic characteristics were of special interest. As part of this research, Dominik Hornel (2002) described a neural network system for analyzing chorales, in which 'harmonic expectations' are central measurements. The analyses are based on probability calculations.

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[18] Quantization of temporal patterns is the subdivision of these temporal patterns into small finite increments. These increments are also called "grids". In this project, quantization is used to objectively measure deviations of performed note values from the notated tone durations.

Hornel showed how this neural network system could be used to falsify the authorship of a chorale attributed to Johann Sebastian Bach.

Concluding Remarks

While analytical methods drawn from statistics and information theory dominated up to the end of the 1970s, other approaches became more important around 1980 and thereafter; among them are transformational and Schenkerian analyses as well as cognitive and Artificial Intelligence approaches. During the 1990s, computer-assisted music analysis became more oriented towards performance-based analyses in connection with cognitive and Artificial Intelligence.

A few conclusions can be drawn from studying the history of computer-assisted music analysis with regard to music cognition:

- Though many publications are of little value, some of them make important contributions and deserved to be more widely disseminated. However, even with newest cognitive research and research in the area of Artificial Intelligence, the proportion of expenditure to benefit is in most cases unsatisfactory.

- More complex analyses in the sense of interactive methods - comprising traditional, sociological, psychological / cognitive, and historic-cultural aspects - show that neither a pure 'traditional' nor a pure computer-assisted analysis produce valuable results. Instead, computer-assisted music analysis needs to use both computational *and* traditional methods.

- Using methods derived from linguistics and from theories of structural levels, computer-assisted music analysis is based on 'traditional' music theory - in the sense of studying musical structures. Some successful research showed that the computer makes it possible to verify the analytical results and algorithms by using the reverse process, generating compositions.

- Finally, computer-assisted music analysis in the field of Artificial Intelligence is much more interdisciplinary. Especially the strong integration of psychological and cognitive aspects of music allows theorists to focus on basic human activities: on the creation of knowledge as well as on processes of composition and perception. This kind of research then focuses more on the philosophical question: How can I know / discover myself and the world?

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