THE COMPUTER AS A
MUSICIANSHIP TEACHING AID

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by

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Beethoven through the "eye" of a computer.
ABSTRACT

Computer programs have been developed to assist music educators in three fields: aural training, traditional harmony instruction, and piano teaching. The computerized aid is incorporated in a small computer with graphics capabilities, which features an electronic organ as an input/output device.

The computer programs developed for administering aural training, interactively adapt to the weaknesses of individual students. And as a result of a convenient new method for entering the instructional material on the organ keyboard, the instructor and lesson designer are spared the need of learning tedious note-encoding techniques.

Other computer programs help assess students' four part harmony exercises, which are entered on the organ keyboard. The printout indicates occurrences of standard harmony "errors", and provides an alternative harmonization based on the student's work, but without the errors. Two new techniques for analyzing keys and estimating root pitches are employed; and a context-based analysis of Bach Chorales is described.

In an extension to the assessment programs, a system has been developed whereby a melody played on the organ keyboard is interactively harmonized. The voices are chosen according to standard harmony "rules", Piston's (1949) table of usual root progressions, and musical guidelines. The musician has interactive control over the choice of chords, root pitches and passing notes.

Slowed-down playback by the computer programs, together with a special visual display of the music (both developed by Tucker, 1977) are used to reveal details of piano playing beyond the scope of existing aids. As with the Aural Training and Harmony Assessment systems, examples are given of the computer's application in a teaching situation. The thesis concludes by describing a concert pianist's reactions to the computer's revelations about his playing.
"And grant that a man read all ye books of musick that ever were wrote, I shall not allow that musick is or can be understood out of them, no more than the taste of meats out of cookish receipt books."

R. North (1653-1734)
in The Musical Gramarian, 1728
PREFACE

The work reported in this thesis forms part of an interactive, computerized aid for musicians. The aid has been developed in the Electrical Engineering Department of the University of Canterbury, under the overall supervision of Professor R.H.T. Bates and with the technical guidance of W.K. Kennedy. As the history of the project is outlined by Tucker (1977) in a companion thesis, only the more important developments are mentioned here.

The prototype "aid" comprised an old upright piano, fitted with a contact switch for each note, and connected to the department's E.A.I.590 computer. Functioning as a music typewriter, it displayed in a primitive form of musical notation, music which was played on the piano. During the following years, Tucker improved the music typewriter to its present state which allows music played on an electronic organ (successor to the old piano) to be displayed on a screen. This score is then interactively edited, and the result is displayed and may be punched out on a paper tape in a special code. As a final refinement, Howarth (1977) developed computer programs which receive as input a paper tape produced in the above manner. His programs permit elegant music copy to be produced using the CALCOMP plotter in the University of Canterbury's Computer Centre. Examples of music printed in this way appear throughout the thesis, and a composition by Norman (1977) has been published using the above process.

During the development of the music typewriter, the computerized aid was extended to help composers in other ways. In mid-1974, composer Susan Frykberg began experimentally using the computer as a composition aid and generator of musical ideas. She developed computer programs which helped her explore the uses of randomness and permutations in music. In a report (Frykberg, 1978) she describes her use of the computerized organ, which functions as a "music interface" between the computer programs and the composer.

To enable a composer to experiment with new sounds and interactively combine them into compositions, a sophisticated synthesizer was designed and incorporated in the system. First Tucker, then Vaughan (1977) and Cheyne (1978), developed a facility whereby two notes, each with a different timbre, pitch, attack, decay and tremolo can be produced concurrently. Notes are controlled either from the computer or from the organ keyboard. This synthesizer is presently being extended.

A method of pitch estimation has been developed by Tucker and Bates (1977, 1978) which enables notes, sung or played into a microphone, to be input directly to the computer programs.

My involvement with the project began in 1973 when I commenced
Canterbury. These meetings provided many valuable ideas for my research, especially in connection with the work described in Chapters 4 and 5, and augmented the grounding in music theory gained in my undergraduate music studies.

The work reported here has used many ideas derived from my experience as a semi-professional orchestral violinist. Chapters 3 and 6 have also benefited from my teaching and playing of the piano (including solo, chamber music, and concerto performances).

In 1976 I began weekly meetings with Dr. J.H.Andreae who supervised my use of his predictive analysis programs. They are used in the investigation of Bach Chorales which is described in Chapter 5 and Appendix 3. These discussions have given me invaluable insights into the remainder of my work.

The characteristics which distinguish the interactive aid for musicians are its comprehensiveness, its interactive features, and its ease of operation. Applications of the system presently include music typewriter, composition aid, music synthesizer, pitch analyser, and musicianship teaching aid. This thesis focusses on the last of these uses. It concentrates on computer-assisted instruction in the fields of aural training, four-part harmony, and piano performance. Also discussed are algorithms for music analysis, and interactive composition in a style predetermined via computer programs. The following papers relating to work reported in this thesis have been prepared for publication:


ACKNOWLEDGEMENTS

All of the people referred to in the Preface have been a stimulus to the work reported in this thesis. I would like to thank them all most warmly, particularly my colleague, Warren Tucker. I am especially grateful to my supervisor, Professor Richard Bates, for his continual guidance and enthusiasm. Dr. John Andreae and Bill Kennedy, my associate supervisors, have patiently and generously rescued and encouraged me.

Always helpful too, have been the Engineering Library staff. The assistance of the University Grants Committee in the form of a Postgraduate Scholarship is gratefully acknowledged. Finally, special thanks are due to Systems and Programs (N.Z.) Ltd for enabling this thesis to be typeset by computer.
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1. INTRODUCTION

1.1. COMPUTER AIDED INSTRUCTION IN MUSIC

The last ten years have witnessed the widespread development of the computer as a teaching aid, in subjects ranging from medicine (cf. Taylor, 1976) to mathematics (cf. Howe and Cassels, 1974). During the same period, computers have been increasingly used for a variety of purposes in the field of music (cf. Tucker, 1977). However, the computer is still not fully accepted as an aid in the teaching of music. Areas which have featured in exploratory work include computer-assisted instruction (C.A.I.) in music theory, sight-singing, aural perception, composition, and performance.

A major drawback of many existing computer-based teaching systems lies in the design of the man-machine interface. For example, a frequently used method for inputting music to computer programs is to encode the music into alphanumeric characters. Thus the music teacher wishing to specify computer-student interaction involving music output must first learn how to use the relevant encoding system (Hofstetter, 1976, p. 26 summarizes numerous such systems in current use). Similarly, the student required to respond with music must usually do so on a conventional typewriter, using alphanumeric characters. It follows from this that the interaction between musician and computer tends to be unnatural, and is often inconvenient for both teacher and student. Probably as a result, the range and depth of the subject matter being taught using the computer have been limited considerably. These limitations are outlined in Chapter 2.

In Smoliar's (1973) view, the first requirement for any computer music facility is that it be convenient and flexible to use. In addition, since creativity is the province of the musician and not of the computer, any C.A.I. which deals with creativity must include interaction with the (human) teacher. Since no music C.A.I. system yet reported seems to involve more than a "housekeeping" type of interaction from the supervising teacher, existing programs cannot deal with creativity. Thus the prerequisites for a system of C.A.I. in musicianship must include facilities for interaction with the teacher. In addition, the system should incorporate a conventional musical instrument and be convenient and flexible to use.

1.2. RATIONALE AND SUMMARY OF THESIS

This thesis describes a system which meets the above requirements. The necessary hardware and associated software have been developed by Tucker (1977) (see also Tucker et al, 1977).
Computer programs designed and developed by the author have been used to increase the present depth and range of C.A.I. in the areas of music theory, aural training and piano performance. Unlike most other C.A.I. courses, the aim is not to usurp the role of the human teacher. Instead, aspects of music teaching which are tedious and mechanical are relegated to the computer, thereby leaving the teacher free to deal with the more creative aspects. Thus the work described here is oriented towards the following: (1) C.A.I. systems in which the interaction between computer and musician is flexible, convenient and adaptive (with respect to the student); and (2) the software manipulation of music for input, output, analysis and composition.

This thesis is organized as follows: Chapter 2 provides a brief history of mechanized aids in the teaching of music, culminating in an assessment of the various computerized aids presently available.

In Chapter 3 it is shown how aural training is broken down into a hierarchy of skills - interactive C.A.I. programs are constructed accordingly. These programs teach a wide range of multiple-choice tasks. The programs enable a student's specific hearing weaknesses to be pinpointed and corrected. In addition, a novel way of specifying the computer-student interaction has been devised which, unlike most existing C.A.I. programs in music, requires very little knowledge about computers.

In Chapter 4 it is shown that the analysis and constructive criticism of arbitrary four-part harmonizations can be obtained directly from the computer. Music is input and output in a "natural" manner. The system has been used successfully with undergraduate classes.

Chapter 5 describes how harmony rules, combined with a novel formalization of musical guidelines, can be used to synthesize a style of music based on that of J.S.Bach. Inadequacies in the programs' harmonizations are corrected interactively by the musician. Problems of style and musical context are discussed. A context-based method for investigating Bach's compositional style - employing the predictive programs of Andreae (1977) - is described.

Chapter 6 shows how a special type of musical notation (cf.Brown,1959) combined with a keyboard input to the computer (developed by Tucker, 1977) has been used to analyse aspects of piano playing that are beyond the scope of traditional teaching aids. In particular, the programs facilitate the analysis of articulation, rhythm and duration, immediately after a performance. The computer is shown to complement the feedback provided by traditional aids (e.g. the metronome and the tape recorder). Finally an interactive session is reported, showing the favourable reactions of a virtuoso pianist of international repute to the computer programs' feedback about his playing.

Chapter 7 summarizes the conclusions of the thesis, and suggests areas for further research.
2. HISTORY OF MUSIC TEACHING AIDS

2.1. INTRODUCTION

Over the centuries, a number of different aids for teaching music have been developed. Those that are of a mechanical nature are described in the next section. Applications of non-computerized aids are then discussed. This is followed by a review of the use of computers in the teaching of music. Areas of instruction that are discussed include aural training, sight singing, melodic dictation, music theory, instrumental performance, music analysis, and composition.

2.2. DEVELOPMENT OF MECHANICAL AIDS

The earliest aids for the teaching of music took the form of "tutor" books such as Couperin's (1716) "L'Art de Toucher le Clavecin". Similar treatises followed (cf.Quantz, 1752; Leopold Mozart, 1756; Clementi, 1801), each of which usually contained an outline of performance techniques together with exercises for the student. Later, exercises of this nature often appeared without an accompanying didactic text. They range in difficulty from the straightforward "study" (cf.Kreutzer, 1810; Czerny, 1839) to the difficult "etude" (cf.Chopin, 1829; Debussy, 1916) to the virtuoso "caprice" (cf.Paganini, 1802) to the "transcendental etude" (cf.Liszt, 1852). Among the didactic texts that do not incorporate exercises are the books by Kullak (1893), Matthay (1903) and Kochevitsky (1967). Such texts usually discuss performance techniques in detail, giving advice to the student.


The first mechanical aid for musicians seems to be the metronome, which was invented by Loulie in 1696 (cf.Scholes, 1950, p.522). Since this invention was 6 feet tall, it did not receive widespread use until the introduction, by Maelzel in 1814, of the more compact, clockwork model. This device produces regular clicks at a rate which is set by the user (available rates usually range from 40 to about 200 clicks per minute). It thereby enables the tempo (or speed) of a piece of music to be set or to be checked for fluctuations during performance. Blom (1958, p.364) considers that "all music which is alive and breathing must be subject to slight variations in pace. It is a fallacy to suppose that any musician should play or sing to the metronome, and teachers who encourage this are to be regarded with suspicion". Nevertheless, the metronome provides valuable feedback about one's performance, as is argued in Section 6.2.
While clockwork metronomes were being introduced to the world, another device - the chiroplast - was gaining increasing use by pianoforte teachers. Invented by Logier in 1814, this apparatus comprises a framework which is attached to the piano at each end of the keyboard (cf. Grove, 1904, p.263). Over the ends of the piano keys are two parallel rails through which the hands are placed. Called "wrist rails", they keep the wrists from moving up or down. This was in accordance with one of the piano-teaching techniques then in vogue - "Moscheles, up to the 1860's, was still teaching that one should play passages with a glass of water balanced on the wrist" (Scholes, 1950, p.725). About six inches behind the wrist rails are two brass frames called "finger guides", each with five slots in it for the pianist's fingers to go through. These finger guides are suspended just above the keys by a brass rod, along which they can slide (from high notes to low notes, and vice versa). The slots in the finger guides prevent the fingers from moving in any but a vertical direction. Consequently, the chief drawback of the chiroplast is that the thumb cannot be passed under the fingers, nor the fingers over the thumb - two manoeuvres required for most piano playing (as is pointed out in Section 6.5). Finally, the chiroplast has a "stout brass wire" pressing against the outside of the wrist to keep the hand in its proper position relative to the arm" (Grove, 1904, p.264)! Despite intense opposition, this restrictive apparatus was used extensively by teachers in Britain, France and Germany for about fifty years (cf. Grove, 1904, p.264)!

A much simplified version of the chiroplast, called the "hand-guide", was produced by Kalkbrenner in 1818. Comprising only the lower wrist rail (described above), it allows the thumb to be passed under the fingers and gives the wrist greater freedom of movement than is possible with the chiroplast (cf. Grove, 1904, p.265). In 1821, Hawker produced a different variation of the chiroplast in which each finger guide is replaced by a sliding wooden mould, shaped to fit the palm. The mould is strapped to the hand in a way which allows free movement of the thumb under the fingers (cf. Grove, 1904, p.265). Although neither device is as restrictive as the chiroplast, both Hawker's apparatus and Kalkbrenner's hand-guide limit the player's wrist movements to such an extent that they cannot be used with many twentieth century pianoforte techniques, such as those described by Matthay (1903) and Kochevitsky (1967).

A more ephemeral "aid" than those described above was the unfortunate mechanical contrivance invented by Schumann in 1832. Designed to increase the span between adjacent fingers, it comprised blocks which were strapped between the fingers (cf. Blom, 1958, p.531). Its use resulted in permanent injury to Schumann's hands, thereby abruptly terminating his piano-playing career at the age of 22.

The next aid to appear seems to have been the digitorium. Designed by Marks for exercising and strengthening the fingers, it is intended for the use of pianists and all other musicians "who require flexible and well-trained fingers" (Grove, 1904,
It consists of a small box, about six inches (15 cm) square, fitted with five piano-like keys mounted on strongly resisting springs. These keys are for musicians to perform five-finger exercises on. In addition, attached to the sides of the box are "certain appliances for stretching the fingers"(1) and a support for the wrist. Such gadgets are totally out of fashion nowadays, but in the middle of the nineteenth century they were quite in vogue. According to Jackson (1865) "no student ought to begin to learn or to play the piano, violin or other musical instrument... before having set the joints of his fingers and hands in order by means of preparatory gymnastic exercises". Jackson further recommended that such exercises should be done both with and without mechanical aids.

After the digitorium came the dactylion. Invented by Herz, it consists of ten rings on strings suspended from springs. A pianist's fingers are inserted through the rings. During playing, each finger moving down to press a piano key must overcome the pull in the opposite direction due to the spring. Although obsolete now, the dactylion enjoyed widespread use as a finger-strengthenener in Germany and the United States in the 1880's (cf.Kochevitsky, 1967, p.5).

The next device to appear was the Virgil Practice Clavier, here referred to by its more common name of "practice clavier" (cf.Scholes, 1950, p.989). Invented at the end of the 19th century, it comprises a piano keyboard without any sound-producing mechanism except that which is used to provide a click either when a note is depressed or when it is released, or both, as desired. In addition, the degree of resistance of the keys can be regulated. By listening to the clicks, a performer can check the synchronization of notes and monitor the raggedness of cutoffs. Also, finger muscles can be strengthened by progressively increasing the resistance of the keys during practice sessions. The benefits and limitations of this device are more fully discussed in Section 6.2.

The next aid to be invented seems to have been the tape recorder, an apparatus for recording sounds on magnetic tape and afterwards reproducing them. Requiring a modicum of technical expertise to operate, this device can be used to analyse aspects of a teacher's or student's performance, as is explained in Sections 6.2 and 6.7.2. The most important advantage derived from the use of the tape recorder, in the view of James (1973), "is that the student learns for himself that what I have been saying all along is really true". Indeed, the tape recorder is convenient, comparatively inexpensive and easy to use. Its only real disadvantage is the time required to rewind back to - and find - a desired extract, before replaying it.

For many years it has been customary for school music teachers, when presenting melodies to their classes, to use large staves painted on blackboards with the melodies superimposed in chalk (or washable ink). A variation on this is the Music Board, which consists of a large set of staves which have been electronically treated so that whenever a stave line (or space) is touched with
a special metal stylus, a note of the corresponding pitch is sounded. If sharps or flats are desired, they must be pre-set (using tuning switches). Thus the Music Board can be used for the presentation of tonal melodies that do not modulate i.e. change key (modulations cause problems, since for each change of key it is necessary to adjust the tuning switches). It is particularly useful for teaching music notation to beginners, since it directly relates pitch to position on the stave.

A more sophisticated aid is closed-circuit television (CCTV) which, when connected to a video-recording device, allows actual or recorded scenes to be reproduced on a screen. As a result, singers' grimaces, pianists' affectations and conductors' normal gestures can be observed afterwards, and the necessary adjustments made. Lehmann (1973) when using CCTV for the teaching of pianoforte and singing, reports that in the course of a single training session "one singer surpassed anything she had ever done": previously uncommunicative before an audience, she "now relaxed, allowing her face to live the words of the aria and displaying a corresponding gain in vocal richness and intensity". Lehmann also uses CCTV to point out to pianists any involuntary movements and muscular tensions which detract from their playing. A drawback of CCTV is that it requires expensive equipment and a reasonable level of expertise in lighting and filming techniques. More recently, a portable, battery-powered videotape recorder with a hand-held camera has become commercially available. This can be operated in any well lit room, with the ease of a tape recorder. It offers all the benefits that CCTV can provide, and seems especially suitable for the detection and correction of faults in a musician's posture.

Educational films play an important role in class music teaching, providing valuable information that the teacher normally cannot present. For example, the history, performance techniques and repertoire of a musical instrument can be explained on the screen by experts. During a 40 minute, 35mm film, students can observe the development of the modern clarinet from the early French chalumeau, and hear musical examples demonstrating various styles and performance techniques, as played by international virtuoso Jack Brymer (cf.N.F.L., 1976). Similar films deal with other orchestral instruments and the piano. Further subjects covered by films (cf.N.F.L., 1976) include ballet, opera, creative dance, and musical notation (the last of these is imaginatively presented using animated cartoons). The main limitation of films is that suitable ones may not always be available. And when selecting a film the teacher may not be aware of all that it contains. Thus there is a risk of presenting information which is undesirable (e.g. outdated performance techniques) or which is too advanced for the class to understand.

In recent years, several self-teaching aids have become available. A rather curious example takes the form of a playback device with a slot in the top. One of a series of cards is inserted in the slot. Each card has musical notation printed at the top, and the corresponding notes are recorded on a magnetic strip at the bottom. Thus the student may learn notation by
watching the printed music and hearing it played at the same time.

Complicated teaching devices have been designed to aid individual study in carrels (a carrel is a cubicle in which one person may study in privacy). Tape recorders may play back teaching material - and operating instructions - relating to slides, films, or videotape cassettes which are available in, or adjacent to, the carrel. A further refinement involves the recording of special pulses on another track adjacent to the soundtrack (on a magnetic tape). During playback, these pulses trigger slide or film presentations which thereby synchronize with the speech or music on the soundtrack. Similar pulses can be stored on films or videotapes, and used to control the playback of associated tape recordings. As a result, music instruction may be presented by means of two cassettes - one audio, the other video - which provide synchronized sound and vision for up to half an hour's duration. The "pulse" track on the audio tape allows the film either to run continuously, or to halt on given frames, or even to skip certain sections. Different presentations can be made with the same video cassette by using several audio cassettes, each with a different set of controlling pulses.

None of the self-teaching aids just described is interactive - the student's role is that of a passive observer. By selecting the material that is presented so as to accommodate the requirements of individual students, the teacher can use these aids for administering remedial tuition. They can also be used when there is no teacher available. It is argued in Sections 2.4 and 3.4 that self-teaching can be made more effective by the use of interactive aids. In particular, it is shown how the computer is used to monitor a range of student responses and react to them in different ways. For example, Section 3.3.4 explains how a computer program monitors student responses to aural tests and reacts by focussing attention on each student's particular problems (of aural perception).

Finally, an ingenious teaching aid has been developed by Kaplan (1973). This electronic device uses pressure-sensitive transducers to monitor the following functions on orchestral stringed instruments: the position of the instrument, the position and tilt of the bow, the angle of the left hand and the spacing of the fingers. When a mistake is made, a buzzer sounds until the error is corrected. This device is designed for teaching beginners. It is unsuitable for use with moderately elementary performance techniques such as "sul tasto" playing or position changing (these techniques are explained in R.S.M., 1958). Methods for providing information about other aspects of instrumental performance are suggested in Section 6.7.2. In particular, intonation, dynamics and rhythm are considered there; and another device - the stroboscopic tuner - is described.

Other devices used in the teaching of music (e.g. the computer and the tachistoscope) are discussed in the following sections, in which experiments relating to work reported in this thesis are evaluated.
2.3. APPLICATIONS OF NON-COMPUTERIZED AIDS

2.3.1. PERFORMANCE

One of the earliest reported experiments involving the use of a machine in the teaching of music was carried out by Cookson (1949). He uses the tape recorder as an aid in self drill i.e. students play music into the tape recorder, and listen to the playback for mistakes. The additional information about one's performance that is gained in this way is referred to as "feedback". Sections 6.2 and 6.4.2.2 outline the benefits to be gained as a result of using feedback provided by the tape recorder.

2.3.2. AURAL TRAINING

Spohn (1959, 1963) has extended the use of the tape recorder by devising a crude form of programmed learning for aiding the development of aural perception of melodic and harmonic intervals. Students self-administer six sets of tests, each set containing 48 ascending melodic intervals. The intervals involved are the following, arranged in order of increasing difficulty as determined by Ortmann (1934) and Poland (1960) (m=minor, M=major, P=perfect, A=augmented): P8, m2, M2, m3, M3, P4, A4, m6, P5, M6, m7, M7. Of the six sets of tests, Sets 1, 2, and 3 consist of pre-recorded examples of the first four, second four, and last four intervals, respectively, of the above group. Sets 4 and 5 contain examples of the first six and last six intervals, respectively; while Set 6 comprises examples of all the intervals listed above. During instruction, an interval is played once to the student, who then has several seconds in which to respond by writing down the name of the interval. The tape recorder then names the interval and replays it. Only after achieving a score of 97 percent (!) is a student permitted to proceed to the next set of tests. Otherwise, the current set is repeated.

The immediate verbal and musical feedback is a valuable feature of Spohn's system. However, it is explained in Section 3.4 that an interactive approach which incorporates immediacy of feedback is more beneficial to the student.

Spohn found in the pretest-posttest evaluation of his experiment, that students in general, experience greater difficulty naming harmonic intervals than naming melodic ones. In fact, one group of students improved their recognition of melodic intervals without making any improvement at all with the harmonic intervals. The implications of this discrepancy for remedial aural training are discussed in Section 3.5. A way of reducing this imbalance is demonstrated there.
2.3.3. SIGHT-SINGING

In the imaginative use of a visual aid, Hammer (1963) showed that a tachistoscope can help with the teaching of sight-singing (i.e., the skill of singing a melody at first sight from the musical notation). A tachistoscope is a device which, when attached to a slide projector, controls the length of time and the brightness with which a slide is displayed. Hammer uses 31 slides, arranged in order of increasing difficulty. They begin by dealing with elementary concepts of pitch "direction", progress to common tonal patterns (as compiled by Petzold, 1960) and culminate in musical phrases of three or four bars duration. When teaching students to sight-sing a series of tonal patterns, the following procedure is employed:

1. project the first pattern on the screen (continuously) while students practise singing it;
2. flash this pattern onto the screen several times, each of .01 second duration;
3. present several more tonal patterns in the manner outlined in steps (1) and (2);
4. flash all these patterns in random order onto the screen, each for .01 second duration.

In this procedure, the tachistoscope is used in conjunction with the traditional classroom music-teaching facilities of piano, blackboard, and manuscript paper.

The reasons for using a tachistoscope are not given in Hammer's paper. From his description of the teaching procedure (as summarized above) it seems likely that use of the device results in eye movements being minimised, thereby increasing the speed of recognition of melodic patterns. Since the tachistoscope is particularly useful for reducing unnecessary eye movements (as in the teaching of "speed reading", for example) it is not surprising that Hammer found the use of tachistoscopic techniques effective for teaching sight-singing. He found, in addition, that the students who benefited most from this approach were those who were more musically talented, and also those that were less intelligent! It is suggested in Section 6.5.2 how tachistoscopic techniques may help pianists who experience difficulty with sight-reading.

2.3.4. MELODIC DICTATION

Following the groundwork of Clough (1961) and Sherburn (1961) who experimented with programmed aural training, Carlsen (1964) designed a course of programmed learning in melodic dictation. This course uses a tape recording of melodies played on a piano. Each student works alone, using an automatically-repeating tape recorder and a programmed book instead of a teacher. The instructional material is arranged in a sequence of increasing
difficulty. Students are divided into two classes: a "linear programming" group which uses all the teaching material in sequence; and a so-called "branching" group which skips certain sections of the teaching material unless an error is made. In the latter event a student is directed (by the programmed book) back to work that was skipped. The term "branching" refers to the process by which one of several possible presentations of the teaching material is selected according to the responses made by the student. Carlsen found that neither group made significantly greater progress than the other. He also concludes that melodic dictation can be taught more successfully using programmed instruction than by the traditional (teacher/classroom) approach.

Since programmed instruction requires logical organization of the teaching material with all branching clearly and unequivocally defined, it lends itself readily to computerization. With melodic dictation, both the stimulus and the response comprise music, either sounded or notated. Hence, before melodic dictation can be taught by using computers, an appropriate music interface must be constructed. A computerized method for melodic dictation (which uses a music interface developed by Tucker, 1977) is described in Section 3.5. The teaching strategy which has been adopted is essentially the same as Carlsen's "linear programming" method. This method is attractive since it involves less work for the teacher, and Carlsen's findings indicate that it may produce results comparable to those obtained using the more complicated "branching" methods.

At the 1965 National Conference of Music Educators held in Washington D.C. it was recommended that "greater emphasis should be placed on individual learning of aural skills, particularly through the use of programmed instruction and audiovisual devices" (Basset et al, 1965). At this juncture the computer entered the scene.
2.4. COMPUTERIZED TEACHING AIDS

2.4.1. REASONS FOR USING THE COMPUTER

When explaining the need for the use of devices such as computers to help teach music, Spohn (1963) writes: "The teaching materials used in fundamentals of music classes have been developed from a predetermined standard that has existed for many years. The presentation of these materials is generally stereotyped. The result has been that the best students meet the [course] requirements with apparent ease and seldom do more, while the students with little pre-college [i.e. pre-university] background struggle with little or no success. The results of this teaching are often frustrating to both teachers and students."

Two basic problems associated with traditional methods of teaching music in classes are identified by Ihrke (1963) as the problem of delayed and imprecise feedback, and the problem of non-individualized pacing of the subject matter (the term "pacing" here means adjusting the rate of presentation of instructional material to the student's capacity to take it in). The first problem is due to the teacher not being able to attend to every student in the class at once. Students must wait to have their work assessed, and the teacher may be too fatigued to assess it accurately (such lapses occur, for example, in the experiment reported in Section 4.5.1). The second problem arises because the rate of presentation of instructional material is usually too slow for some students, and too fast for others. Since computers are essentially fast, logic-based machines, they have the potential for providing immediate, precise feedback. Moreover, for the reasons given in Section 2.3.4, computers are suitable for providing the individualized pacing offered by programmed instruction. Therefore, for those aspects of class music instruction that can be represented by computer programs, such feedback and individualised pacing may be used to overcome the two problems identified by Ihrke. In these ways, computers can help reduce the frustration noted by Spohn (see the first paragraph of this section).

Chapter 3 explains how a computer is used for aural training. Feedback is immediate and the curriculum is designed to provide individualized pacing. The results presented in Section 3.5.1 indicate that the computer helps to overcome both of the problems identified by Ihrke (1963), for class aural training. Chapter 4 explains how a computer is used to assess a student's four-part harmony exercises. Feedback is meticulous, and can be immediate, as is described in Section 4.4. The experimental results presented in Section 4.5 show that the computer can help overcome Ihrke's first problem (of delayed and imprecise feedback), for class harmony teaching.

In Ihrke's (1963) view (and also the author's) the music educator can use the computer to "eliminate the tedium of individual drill and exercising of the students, and instead turn his [or her] attention to means whereby students with a repertoire of precise
knowledges [sic] and concepts can employ these ideas in creative listening, performing, and composing." Ihrke feels that, in order to derive maximum benefits from the use of the computer, "two new teaching techniques are called for - one a meticulous ordering of the training material, and the other an equally meticulous assignment of material to the student". In the development of the musicianship teaching aid described in this thesis, the first of these techniques has been adopted as a guideline. And during the course of the training sessions described in Sections 3.5 and 6.6, the author has come to realize the importance of Ihrke's second technique.

2.4.2. COMPUTERIZED TEACHING OF SIGHT-SINGING

An initial attempt at computerized music teaching was made by Allvin and Kuhn (1967). They interfaced a pitch estimator (i.e. a device which outputs the pitch of a note that is sung or played into it) to a computer, for the purpose of teaching sight-singing. A sequence of elementary sight-singing exercises, tests and branching criteria are first encoded in a computer language especially designed for music instruction. Then, the musical notation for the exercises and tests is converted into photographic transparencies. These are stored in a device called an "image file", which enables any transparency to be automatically displayed when requested by the computer programs. An instructional session begins with a musical exercise being displayed in this way. If requested, the programs play the music on a computer controlled sound-generator, before the student attempts to sing it into a microphone in time with a metronomic pulse. Exercises and tests are limited to only five notes each, with every note lasting about two seconds! Depending on the accuracy of the student's response (as determined by using the pitch estimator) the computer programs either administer the same exercise again or proceed with the next one, or present similar material for additional practice.

Immediately after singing a test or exercise, a student is told which notes are out of tune and which ones are completely wrong. The criterion for judging whether a note is out of tune is selected by the student as being either two percent or four percent deviation from the correct pitch. But Allvin and Kuhn do not indicate whether the pitch is calculated by using the beginning or end of a note, or whether it is estimated as an average over the entire note. This omission is unfortunate because, with the former method of calculation, the use of vibrato or portamento could cause a correctly pitched note to be registered as an error. With the second method of calculation, a wrong note that is immediately corrected by the student would probably be registered as an error by the programs. Vibrato, portamento, and immediate error-correction are not generally considered to be mistakes, by many sight-singing instructors.
During training sessions, Allvin and Kuhn's programs calculate and store the following details about each student:

1. the number of times a request is made to hear the music replayed;
2. the number of out-of-tune notes, as distinct from
3. the number of completely wrong notes that occur; and
4. the number of occasions on which the student fails to keep in time with the metronomic beat.

These figures are used when branching occurs, although the way in which they are used is not explained by Allvin and Kuhn. These figures are also employed in the subsequent analysis of the student's results. In Section 3.3, aural training programs are described which calculate similar details. For example, a comprehensive record of each student's mistakes is used to interactively direct the computerized teaching towards his or her specific weakness(es). Also, the request rate for replays is printed after each training session as a measure of the student's confidence.

In the very elementary exercises and tests administered by Allvin and Kuhn's programs, ten students experienced the following order of increasing difficulty (the abbreviations are the same as those defined earlier, in Section 2.3.2): m2, m3, P5, M2, P4 & M3, A4. This order differs considerably from that obtained by Ortmann (1934) and Poland (1960), which was used by Spohn (1963) (see Section 2.3.2). A reason for this discrepancy is suggested in Section 2.4.4, in which it is also explained why an interactive approach would probably improve the effectiveness of Allvin and Kuhn's computerized teaching.

It is perhaps surprising that, following Allvin and Kuhn's successful use of a pitch estimator interfaced to a computer, nearly ten years elapsed before musical performance was once again input directly to pedagogic computer programs. One reason for this hiatus must be the difficulty associated with designing computer programs to interpret the durational and rhythmic information (Allvin and Kuhn avoided this problem by having each student sing notes all of the same duration, in time with a metronome). More recently, Peters (1976) has established the feasibility of inputting instrumental performance to the computer, and we (Tucker et al, 1977) have developed a comprehensive computerized system which accepts input from a wide range of musical instruments and voice (a new, efficient pitch estimator has been developed by Tucker and Bates, 1977, 1978). The latter system copes with many of the problems of interpretation mentioned above; and its applications in the teaching of musical performance are evaluated in Sections 6.3 to 6.5.
2.4.3. COMPUTER-ASSISTED PERFORMANCE TEACHING

Following Allvin and Kuhn's (1967) work, the next significant study involving the use of the computer in music education was carried out by Diehl (1971). The object of the experiment was to use the computer to help teach the perception of articulation, phrasing and rhythm. During training sessions, programs display musical notation, play pre-recorded musical examples to the student, and ask questions. For example, a student is presented with two clarinet performances of the same melody, only one of which is correct. The incorrect performance has a mistake in either the phrasing, the articulation or the rhythm. After identifying the error, the student has the opportunity of recording (on a tape recorder) a personal performance of the passage. This performance may then be compared with the "correct" version played back by a program-operated tape recorder. Applying concepts and criteria acquired during the automated questioning, students use self-criticism to try to improve their playing.

Diehl's programs cannot provide feedback about performance, since the student's playing takes place independently of the computer (i.e. the musical instrument is not connected to the computer in any way). Nevertheless, the experiment establishes the feasibility of teaching musical judgment by mechanized question-and-answer techniques. It must be remembered, however, that the quality of the judgment being taught depends entirely on whoever is specifying the computer-controlled procedure. There is a danger that the prestige of "The COMPUTER" may, in the naive mind, lend authority to judgments of questionable value presented by way of computer programs.

Mechanical (i.e. non-creative) aspects of instrumental performance are the subject of instructional computer programs developed for the PLATO system (described in Section 2.4.6). Illustrations and textual explanations are automatically presented to the student, who responds to questions about them. The programs present remedial material if the student does poorly, and move on to more advanced topics if the student does well. As summarized by Hofstetter (1976, p.22), subjects taught in this manner include percussion terminology, elementary fingering for the violin and viola, recognition of pictures of musical instruments, and methods of playing wind and percussion instruments. In Gagné's (1977, p.225) opinion "pictures can aid the learning of motor skills [e.g. in instrumental performance] by directing the learner's attention to the external cues for the control of motor responses" [e.g. bowing and fingering]. In other words, pictures can show you what to do, and what not to do. However, as explained by Gagne, this information is of limited use during learning unless it is accompanied by practice (i.e. "repeated attempts to execute the correct movements, followed in each case by informative feedback", Gagné, 1977, p.228). Thus, in order to gain maximum benefit from computer programs designed to teach performance methods, students should practice their instruments during the computerized training sessions. However, since none of the PLATO programs reported by Hofstetter provides feedback about instrumental performance, students are likely to benefit more
from teachers who provide this feedback. (Gagné, 1977, p. 226, considers "One of the most important external conditions for the learning of a motor skill is the provision of informative feedback" - this is a generally accepted principle of psychology.) For the above reasons, these PLATO programs (for teaching performance methods) may be regarded as poor substitutes for the human music teacher. They seem best suited for revision purposes only (Peters, 1975, describes an alternative use of some of these programs - namely to take prospective teachers through the steps involved in teaching instrumental performance).

2.4.4. COMPUTERIZED AURAL TRAINING

The application of computer techniques to aural training was pioneered by Kuhn (1974), who has interfaced an electronic organ to a computer, as an output device. Programs play musical examples via the organ and then ask questions about them on a teletypewriter. Topics covered are summarized in Table 2.2. They range from intervals to modulation. Students have the freedom to choose any of the teaching material that they wish, changing from one topic to another at will. It is shown in Section 3.5 that a systematic, step by step approach is crucial to the success of the aural training system described in Chapter 3. The results presented in Section 3.5.2 suggest that it is unwise to allow students to structure their own courses of study.

With Kuhn's system, a teacher wishing to specify the computer-student interaction must first become familiar with a specially designed computer language. All musical examples must be encoded in this language. The system described in Chapter 3 improves on Kuhn's method of specification, by using an electronic organ to input the musical examples. Thus the teacher (i.e. the specifier of the computer-student interaction) plays the examples - an easier and more natural method than encoding them in a computer language. Moreover, a single computer program is used to teach a wide range of aural training topics (e.g. modulation identification, and interval recognition) in a manner that frees the teacher from the necessity of learning intricate details of computer programming.

Killam and Lorton (1974) present a report on Kuhn's system. In another article, Killam et al (1975) document the use of Kuhn's system in a study of student identification of harmonic and melodic intervals. They find that students experience the following order of increasing difficulty (the abbreviations being the same as those defined earlier, in Section 2.3.2): P8, M3, m2, P4 & P5 & M6, M2 & m3, A4, M7, m7, m6. It is significant that this order differs considerably from that obtained by Ortman (1934) and Poland (1960), as used by Spohn (1963) in his pioneering work (discussed in Section 2.3.2). Completely different again is the order obtained by Plomp et al (1973), namely P8, P4, m3 & M3 & M6 & M7, m6, A4, P5, M2, m7, m2. These discrepancies are easily accounted for by the findings presented in Section 3.5, that aural perception difficulties vary considerably from one student to another. To a lesser extent, the
perceptual problems of a given student tend to fluctuate from time to time. Killam et al (1975) notice the variation between students, but are unaware of the temporal fluctuations since their study involved only one testing session per student. Therefore, in order for an aural training system to provide individualized instruction which accommodates student weaknesses, it must be interactively adaptive so as to take into account the variations described above. To date, the scheme described in Chapter 3 seems to be the only computerized aural training system which incorporates such adaptation.

Hofstetter (1975) has developed a computer system for aural training called GUIDO (Graded Units for Interactive Dictation Operations). According to Hofstetter (1976, p.24) "the basic design of the GUIDO system is the same as that of the Stanford system" (i.e. the system developed by Kuhn, 1974; see also Killam et al, 1975). However, GUIDO's aural training sessions take place on graphics terminals (i.e. computer terminals with a typewriter and a screen for displaying images of music notation, text and pictures). This allows greater flexibility for computer-student interaction than do the typewriter terminals of the Stanford system.

2.4.5. COMPUTER-AIDED INSTRUCTION IN MUSIC ANALYSIS

To aid the teaching of music analysis, Whitney (1975) has developed a conversational computer programming language called SLAM (a Simple Language for the Analysis of Music). This language enables students to obtain analyses of compositions which have previously been encoded and stored inside the computer. Stored compositions include 120 Bach Chorales and a variety of pieces in different styles. Analysis programs have been developed under the direction of Phelps and Poland (cf. Hofstetter, 1976, p.26) to identify chromatic notes and modulations in tonal music. Other programs identify 12-tone rows and their permutations in dodecaphonic compositions. Students may also use SLAM to carry out Hindemith (1970) "chord-tension" analyses, or to compute the frequency of pitch classes and melodic-intervals (cf. Hofstetter, 1976, p.26). Associated programs developed by Hofstetter (1972) catalogue patterns in the melody, harmony, and note durations. They also tabulate the number of times each note occurs in a composition, together with the summed duration of each note's occurrences.

In the above manner, students can use the computer to gain insights into techniques of music analysis.

Appendix 3 shows how a new technique for music analysis is used to investigate aspects of musical context.
2.4.6. C.A.I. IN MUSIC THEORY

Computer programs for instruction in music theory have been developed by Hultberg et al; Green; and Thostenson (cf. Hofstetter, 1976, p.22). These three systems all concentrate on the naming of notes of musical scales, intervals, and chords; and on the identification of keys and chords. A major limitation is that the only mode of communication between students and programs is the typewriter. Since it seems of dubious value to introduce new concepts to students without playing them corresponding musical examples, these three systems are perhaps best suited for revision of material which the students have already studied.

The limiting of student responses to those that can be made on a typewriter, considerably restricts the scope of the instructional material. Diehl (1971) considers that the entry of four part harmony, by the student, on a typewriter terminal "looks to be so cumbersome as to be of questionable value". Chapter 4 describes a computerized system in which four part harmony is input to the programs using an organ keyboard. The programs analyse a student's work, assessing it for standard harmony "errors", which are corrected wherever they occur. The corrected version is based on the student's work and may be played back by the programs, if requested. In the above ways, the system described in Chapter 4 extends the sophistication of the music theory instruction offered by many existing systems.

Placek (1974) has developed computer programs which use the graphics features of the PLATO terminal for teaching aspects of elementary music theory related to rhythm (e.g. note durations and time signatures). The "PLATO [i.e. Programmed Logic for Automatic Teaching Operations] System is specifically designed for individualized education in a computer-based, interactive environment" (Paulson, 1976, page 1.1). An amazingly flexible terminal called a "plasma display terminal" (cf. Stifle, 1971) is used by Placek to display musical notation, messages, and cartoon-type illustrations (the terminal can also display colour images from a computer-controlled, microfiche slide projector). The student responds on the terminal's keyboard, or by touching a designated area on the terminal's screen.

The PLATO system is also used by Wittlich (cf. Hofstetter, 1976, p.25) for teaching set theory, i.e. the techniques developed by Forte (1973) for describing the organization of pitches in atonal music.

In addition, Rickman and Rucinski have developed programs on the PLATO system, for teaching part-writing and jazz chording, respectively (cf. Hofstetter, 1976, p.22). The musical sophistication of their programs is not indicated by the above author.

The educational potential of the plasma display terminal (described above) seems awesome. The recent addition of a computer-controlled sound generator to this terminal makes it especially suitable for presenting the type of theory instruction that the programs of Hultberg et al, Green, and Thostenson...
(described above) deal with. The further addition (to the plasma display terminal) of an organ keyboard for the input of music would enable all the computerized musicianship teaching aids described in this thesis to be implemented on the PLATO system.

2.4.7. C.A.I. IN COMPOSITION

To aid the teaching of electronic composition techniques, Alonso et al (1975) have interfaced a 16 channel synthesizer to a minicomputer. Up to four composition students can learn on the system simultaneously. Each student is initially given an exercise whereby 12 specified sounds and one silence are to be combined into a composition. Successive exercises add more compositional concepts (e.g. repetition) until the student is given complete compositional freedom. In this way the student is made to experiment with a wide range of sonic ideas, thereby gaining a "feel" for electronic techniques.

Embodying a more theoretical approach, the COMPOSE program developed by Nelson (cf. Hofstetter, 1976, p.25) allows music students to experiment with serial structures, probability models, syntax (through directed graphs) and list processing. A drawback of this system is that it requires the user to be proficient in the APL programming language, and it also seems to demand a high level of mathematical competence from the students.

Finally, the ISMUS project, developed under the direction of White (cf. Hofstetter, 1976, p.25) enables music, computer-science and engineering students to collectively compose pieces using a synthesizer controlled by a minicomputer.

<table>
<thead>
<tr>
<th>MUSIC TEACHING AIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Music Board</td>
</tr>
<tr>
<td>Films</td>
</tr>
<tr>
<td>&quot;Tutor&quot; books</td>
</tr>
<tr>
<td>Metronome</td>
</tr>
<tr>
<td>Practice Clavier</td>
</tr>
<tr>
<td>Records</td>
</tr>
</tbody>
</table>

TABLE 2.1 Aids for the teaching of music which are currently available.
<table>
<thead>
<tr>
<th>FIELD</th>
<th>SUBJECTS</th>
<th>FACILITIES</th>
<th>AUTHOR(S)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PERFORMANCE</td>
<td>Recognition and perception of articulation, phrasing and rhythm for flute, clarinet, oboe, saxophone, trumpet &amp; baritone</td>
<td>IG, TTY, MN, Rem. No music input. Pre-recorded music output.</td>
<td>Diehl</td>
</tr>
<tr>
<td></td>
<td>Sight singing</td>
<td>IG, TTY, MN, Rem. Music I/O</td>
<td>Allvin &amp; Kuhn</td>
</tr>
<tr>
<td>AURAL TRAINING</td>
<td>Intervals, triads, melody, rhythm, chords, &amp; modulations</td>
<td>TTY, MN, Rem. No music input. Music output</td>
<td>Kuhn: also</td>
</tr>
<tr>
<td>COMPOSITION</td>
<td>Serial structures, probability models, list processing, and syntax via directed graphs</td>
<td>Non-interactive computer programs.</td>
<td>Hofstetter</td>
</tr>
<tr>
<td></td>
<td>Compositional concepts using &quot;sound objects&quot; (e.g. glissandi)</td>
<td>Computer-controlled synthesizer.</td>
<td>Nelson</td>
</tr>
<tr>
<td></td>
<td>Interactive sound synthesis.</td>
<td>Computer-controlled synthesizer</td>
<td>Appleton, Alonso, and Jones.</td>
</tr>
<tr>
<td>MUSIC THEORY</td>
<td>Clefs, intervals, trichords, tetrachords, scales &amp; modes, key signatures, triads, and chord progressions.</td>
<td>TTY, no MN No music I/O.</td>
<td>White</td>
</tr>
<tr>
<td></td>
<td>Grand staff, ledger lines, octave-transposition signs, intervals, triads, 7th chords, placing chords in keys, altered chords, and modulation.</td>
<td>Printed scores in packets for students.</td>
<td>Hultberg</td>
</tr>
<tr>
<td></td>
<td>Grand staff, ledger lines, intervals, triads, scales, keys &amp; key signatures, primary and secondary seventh chords, Neapolitan 6th chord, augmented 6th chords.</td>
<td></td>
<td>Green</td>
</tr>
<tr>
<td></td>
<td>Set theory (analytical methods for atonal music)</td>
<td></td>
<td>Thostenson</td>
</tr>
<tr>
<td></td>
<td>Notes &amp; rests, time signatures, notation, rhythm puzzles</td>
<td></td>
<td>Wittlich</td>
</tr>
<tr>
<td>ANALYSIS</td>
<td>12-tone rows, permutations, non-harmonic tones, modulations; melodic, harmonic, and durational patterns; chord-tension; pitch class and melodic interval frequency-tables.</td>
<td>Large computer with database of 120 Bach Chorales &amp; other pieces.</td>
<td>Phelps &amp; Poland</td>
</tr>
<tr>
<td>TEACHER TRAINING</td>
<td>Principles of flute, clarinet, bassoon, oboe, saxophone, trumpet, baritone, horn, trombone, euphonium, tuba, and percussion.</td>
<td></td>
<td>Peters</td>
</tr>
</tbody>
</table>

**TABLE 2.2** Computer systems which have been developed for music educators.
IG=interactive graphics TTY=teletype I/O=input & output Rem.=remedial tuition MN=computer-displayed music notation PLATO=PLATO system (which includes IG, TTY, Rem, MN)
2.5. **SUMMARY**

The aids for musical instruction that are more widely used are listed in Tables 2.1 and 2.2. As pointed out in Sections 2.2 and 2.3.1, the metronome and tape recorder provide valuable feedback about a musician's performance. However, it is argued in Chapter 6 that the computer can help musicians by providing different feedback to that offered by existing aids. In particular, the computer can reveal details of fast passages, cross rhythms and legato playing which conventional aids cannot show up. Sections 6.5 and 6.6 explain and demonstrate some of the resulting benefits of this new feedback for piano teachers and performers.

The only computerized aural training system that has so far been designed to adapt to the weaknesses of individual students is the system described in Chapter 3 of this thesis. The need for such adaptation has been revealed in research by Killam et al. (1975). With the computerized aural training system described in Chapter 3 it is much easier for the instructor to devise computer-student interactions than with Kuhn's computerized aural training system, which is described in Section 2.4.4.

As reported in Section 2.4.5, the computerized systems for teaching traditional music theory that have been developed previously to the work reported in this thesis all deal with instructional material of an elementary nature. This is probably due to the limitations imposed by the use of a typewriter as the computer-student interface. The development (by Tucker, 1977) of a versatile interface that is easy and "natural" for musicians to use, has enabled the author to develop computer programs for assessing students' four part harmony exercises. The resulting system, described in Chapter 4, is seen to extend the sophistication and creativity (of student responses) embodied in existing systems.
3. COMPUTERIZED AURAL TRAINING

3.1. RATIONALE FOR USING COMPUTERS IN AURAL TRAINING.

Long regarded as a necessary evil by music students and instructors alike, aural training - that is, the instilling of basic auditory recognition and retention skills - remains one of the fundamentals of musicianship education. It is a subject that is frequently tedious and mechanical to teach, and because of this there have been several attempts, some of them successful, to program computers to aid in the teaching of certain aural skills. Killam and Lorton (1974) and Hofstetter (1975) have used computers to give ear-training drill. Placek (1974) designed and successfully tested computer-assisted instruction in rhythm. Melodic dictation has been programmed by Kuhn (1974). All of the computerized aural training systems to date seem to have two main drawbacks: (1) They do not adapt to individual students' weaknesses, and (2) the setting up of the computer-student interaction requires specialist training in the use of a computer programming language or code. These drawbacks probably explain the paucity of computerized aural training systems actually in regular use. What is needed is a system that not only satisfies the needs of the student, but also requires little specialist training for the teacher, whose creativity and judgment should be complemented, and not restricted, by the presence of the computer. This chapter reports the development of such a system, which in addition has been designed to adapt to the needs of each student.

The next section examines what is involved in aural training in order to determine which aspects are able to be computerized. The operation of the computerized aural trainer is then described, showing how student weaknesses are revealed and concentrated on. It is shown how a teacher can construct a lesson in a matter of minutes, without any special knowledge about computers. Aspects of the teaching-theory involved in computerized aural training are considered in Section 3.4, after which the practical application of the aural trainer in teaching undergraduate music students is described. It is shown how the computer enabled an unexpected perceptual difficulty to be detected and then remedied. Ways in which the computerized aural trainer can be misused are pointed out. Section 3.6 suggests ways in which the programs might be extended to other aspects of aural training, after which Section 3.7 concludes by summing up the findings of this chapter, namely that the computerized aural trainer is a considerable improvement on existing systems, and is likely to be widely accepted because of its ease of use by students and teachers alike.
<table>
<thead>
<tr>
<th>TONALITY</th>
<th>INTERVALS</th>
<th>MELODY</th>
<th>RHYTHM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Identify the type and inversion of a triad</td>
<td>Identify ascending melodic intervals</td>
<td>Hum, sing, or play a melody</td>
<td>Clap or tap a rhythm</td>
</tr>
<tr>
<td>Name the mode of a passage</td>
<td>Sing and name three successive notes</td>
<td>Sing one part of a two part piece</td>
<td>Name the time signature</td>
</tr>
<tr>
<td>Name cadences</td>
<td>Recognise (or name and sing) notes of a major, minor, or dominant seventh chord</td>
<td></td>
<td>Beat time</td>
</tr>
<tr>
<td>Recognise the occurrence of a modulation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Name a modulation</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**TABLE 3.1** Summary of aural tests of the Trinity College London, for grades INITIAL through to VIII. N.B. Each test example is presented twice to a student before a response is required.
3.2. FORMAL DESCRIPTION OF AURAL TRAINING.

Table 3.1 lists the tests contained in a comprehensive, internationally recognised aural training system which is designed for beginners through to advanced musicians (Lovelock, 1966). All the aural tests for grades "Initial" to VIII of the music examinations of Trinity College, London, England, are summarized in this table and divided into their various types.

Consider the TONALITY column which comprises tests of categorisation into conjunctive concepts, culminating in the concept of tonality (conjunctive concepts are those that do not "intersect" or "overlapping", as explained by Bruner et al, 1962). Due to the nature of conjunctive concepts, a student's response is either right or wrong, and can therefore be mechanically assessed by comparison with a stored answer. The student learns to form the required concepts by formulating and testing hypotheses, and by continually modifying his learning strategies. This can be successfully carried out by the musically imaginative student, but traditionally it is the teacher who has suggested the more obvious external strategies (e.g. "Listen to the bass notes when identifying cadences").

The INTERVALS column also involves categorisation: either of pitch, or of the interval between pitches. The student develops the performance skill of singing a note that has just been sounded. The successful categorisation of pitch may be arrived at in two ways: by the reflex recognition of the pitch of a note when it is played (this is the phenomenon known as "absolute pitch" or "perfect pitch") or by calculation of pitch using the interval from a given note. There seems to be no recorded instance of successful teaching of absolute pitch past the age of 10, which implies that the only concept being taught is one of "interval". But the concept of pitch (as opposed to timbre, for example) must be assumed as a prerequisite. As the pitch categories are mutually disjoint (i.e. a note cannot have more than a single pitch) assessing can once again be done mechanically, because the student’s categorisation can only be right or wrong. With interval recognition, the usual strategy adopted is to match the given interval with the start of a familiar tune whose initial melodic leap is known (e.g. "Auld Lang Syne" commences with the leap of a perfect fourth, so that any two notes which sound like the start of Auld Lang Syne must be a perfect fourth apart). Again, this strategy is usually suggested by the teacher.

The RHYTHM tests instil the concept of meter by categorising music into different time signatures. This is reinforced by the student "beating time" during a replay of the test passage. Also, a rhythmic memory is developed, as a student is required to remember and reproduce the pulses and relative durations of the test piece. While it is simple to arrange time signatures into disjoint categories (thereby reducing the assessment of the student's performance to a mechanical task), it is much more difficult to assess a student's rhythmic imitation. The student
can slow down in the difficult parts, or even miss a note out, and still be given a high grade in an examination. Assessment here requires interpretation of the student's response as to whether it is musically secure.

Finally, the MELODY tests start by developing a memory for pitches and intervals (as well as for rhythm) together with the performance skills required to sing or play these. The more difficult tests are designed to instil a concept of melody, by requiring the student to sing or play one of two melodies which are presented simultaneously. If the student is required to sing or hum responses to tests, inadequacies in the student's vocal skills must have an adverse effect on the accuracy of the response. However, this can be avoided if the responses are made on a key-board (with one finger) or, for that matter, on any instrument on which the student is proficient.

3.2.1. ASPECTS SUITABLE FOR COMPUTERIZATION

All the skills and concepts being assessed in the tests discussed in Section 3.2 are summarized in Table 3.2. Consider which of these are suitable for computerised instruction. As just discussed, traditional teaching methods are based on the following:

1. Categorisation into disjoint groups (e.g. pitch classes, conjunctive concepts);
2. Memorisation of a single line of music, or a rhythm; and
3. Development of singing skills.

While it is clear that (1) can be taught by using multiple-choice question techniques, it should also be evident that memory can be developed by playing two similar passages and administering multiple-choice questions about the way(s) in which they differ (cf. Sherman and Knight, 1972). Therefore, all tests in Table 3.1 not involving singing, clapping or beating time can be taught by multiple-choice techniques, which can be easily programmed for a computer because they are essentially routine tasks.

The next section describes a computerized system designed to (inter alia) administer multiple choice questions about music. The necessary musical examples are "played" by computer programs on a versatile electronic organ which is interfaced (i.e. connected) to the computer. This instrument seems ideally suited to function, in a computerized teaching system, as the interface between music students and the computer.
<table>
<thead>
<tr>
<th>TYPE</th>
<th>STIMULUS</th>
<th>RESPONSE</th>
<th>NUMBER OF CATEGORIES</th>
<th>WHAT IS BEING ASSESSED</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tonality</td>
<td>A chord, or sequence of chords and notes</td>
<td>Answer*</td>
<td>2 to 6</td>
<td>More than 20 concepts</td>
</tr>
<tr>
<td>Intervals</td>
<td>Two to four notes within an octave</td>
<td>Answer*; or sing one or all the notes of the stimulus</td>
<td>3 to 12</td>
<td>One concept. Singing skills</td>
</tr>
<tr>
<td>Melody</td>
<td>3 to 20 notes in sequence with up to 2 notes sounding simultaneously</td>
<td>Sing, hum or play the melody of all or part of the stimulus</td>
<td></td>
<td>One concept. Memory skills (Singing skills)</td>
</tr>
<tr>
<td>Rhythm</td>
<td>A sequence of 5 to 20 notes of varying loudness</td>
<td>Answer*; clap or tap the rhythm of the stimulus. Beat time during a replay.</td>
<td>2 to 8</td>
<td>Up to 5 concepts. Memory skills.</td>
</tr>
</tbody>
</table>

TABLE 3.2 Summary of skills and concepts being assessed by tests listed in Table 3.1.

* Denotes a multiple-choice answer, the number of choices (categories) being indicated in the adjoining column.

By a chord is meant three or more notes sounded simultaneously.
3.3. DESCRIPTION OF THE AURAL TRAINER

In this section, the operation of the Computerized Aural Trainer is described both from the instructor's and the student's point of view. But first, since the aural trainer is part of the Musicianship Teaching Aid, itself part of the interactive aids for musicians developed by Tucker et al (1977), the computer system in which all of these aids are incorporated is outlined.

![Diagram of the computerized musicianship aids system]

**FIGURE 3.1 Layout of the computerized musicianship aids system.**

3.3.1. **THE MUSICIANSHIP TEACHING AID COMPUTER SYSTEM**

The computer on which the Musicianship Teaching Aid is implemented is the EAI 590 hybrid system. This comprises an EAI 580 analogue computer linked via a hybrid interface to an EAI 640 digital computer. The latter has only 16K, 16 bit words of magnetic core storage, supplemented by a fixed head disc containing 360K words of memory. Peripheral devices include a paper tape punch, Tektronic 611 storage screen (with a "joystick" cursor allowing points on the screen to be visually identified) and a hard copy unit. There is also a DECwriter console.
typewriter, a DEC magnetic tape unit and an interface called a Binary Data Interface (BDI) - designed for interconnecting a wide range of devices and experimental apparatus with the computer.

An electronic organ has been constructed (cf. Tucker 1977) which can be played either conventionally using the keyboard, or by the computer which interacts with the organ through the BDI. In the latter case, the organ in effect becomes another peripheral input/output device: the depressing of keys on the organ is automatically detected by the computer, which can itself "play" music by switching notes on and off electronically. Tucker (1977) has developed a comprehensive music operating system by which, commands entered on the console typewriter cause music, played on the organ keyboard, to be displayed on the screen (see Figure 3.1). Other typed commands enable music to be stored, modified, and played back, as is explained in the next sections.

3.3.2. Initialisation of the Musicianship Teaching Aid in General, and of the Aural Training System in Particular.

The layout of the essential parts of the Musicianship Teaching Aid is shown schematically in Figure 3.1. It is initialised in the following manner. The user plugs the electronic organ into the BDI and loads the music-system magnetic tape onto disc using the EAI 640 Monitor and magnetic tape utility routines. The core image file PIANO1 is then loaded into core and executed, which causes a brief explanation of how to operate the musicianship aids system to be displayed on the screen, if desired (cf. Tucker, 1977). When the computer is ready to accept commands from the musician, it types "<-".

The use of the operating system (developed by Tucker, 1977) is now illustrated by an example of how it is used by an instructor to set up an aural training module.

3.3.3. Operation of the Aural Trainer by the Instructor

The computerized aural trainer is designed to present a curriculum which is modular in nature. Each module comprises a set of musical examples (e.g. triads) grouped in categories (e.g. major, minor, etc.). The student is asked to choose the category of each example after it is played by the programs (the computer-student interaction is described in the following section). A typical module contains 30 examples of cadences which are played to the student who must identify which of the categories "perfect", "plagal", "imperfect", and "interrupted", each randomly selected example belongs to (the American names for these cadences are respectively "authentic", "plagal", "half", and "deceptive").

When setting up an aural training module, the instructor must decide on the categories to be differentiated between and devise examples for each category. The word "RECORD" is entered on the console typewriter and musical examples, grouped in categories,
are played on the organ keyboard. For instance, an instructor wishing to teach students to discriminate between major, minor, augmented and diminished triads in root position might well play the examples shown in Figure 3.2.

![Figure 3.2 Some test examples for an aural training module designed to teach triad discrimination. Each example (i.e. each triad) is followed by low C (as a marker note), and each category (major, minor, etc.) by a low Db.]

As illustrated in this figure, the bottom two notes of the organ keyboard, low C and low D flat, are reserved for use as "markers". These marker notes are not played back to the student during aural training. They are needed by the programs to identify the end of each example and the end of each category (with sufficient ingenuity it is always possible to find other ways of indicating the ends of examples and categories, but the author finds it convenient to use these two notes as markers). The instructor then types "SCORE," which causes what has just been played to be displayed on the screen.

Being human, an instructor is liable to make mistakes. These are corrected by using the joystick cursor to identify their positions on the screen and then replacing them with the desired notes, which are identified by playing the organ keyboard. Appropriate commands, such as "DELETE", "INSERT", "TRANSPOSE,+5 SEMITONES", etc. must be typed before the organ keys are depressed (this editing process is described in detail by Tucker, 1977; - if desired, only the first letter of a command need be typed). Once all mistakes have been eliminated and the examples
are adjudged satisfactory, "LABEL" is typed, after which the instructor can add any mnemonics or cues that are likely to aid categorisation (e.g. "AULD LANG SYNE" could be associated with "PERFECT 4th") and any helpful instructions (e.g. "Sing the bass notes to yourself"). The completed module is then stored on magnetic tape and is available for use at any later time. Figure 3.3 illustrates the commands used to construct a module designed to teach triad discrimination using the musical examples shown in Figure 3.2.

```
<- RECORD
SCORE
<- LABEL
TEACH1 CI
LD

PLEASE TYPE CATEGORY NAMES (& MNEMONICS).

1 : MAJOR - HAPPY
2 : MINOR - SAD
3 : AUGMENTED - WEIRD
4 : DIMINISHED - DARK

WOULD YOU LIKE TO FILE THIS?

YES
<- FILE,TEST59
FR
MESSAGE
TRIAD RECOGNITION: TRY AND SING THE NOTES TO YOURSELF.
FR
TEST59 DA
<- 
```

**FIGURE 3.3** The operator commands used to set up a typical aural training module, using the musical examples illustrated in Figure 3.2 (these examples are played on the organ keyboard at *). The mnemonics and suggestions typed by the instructor (underlined) are later presented to the student, as is explained in the text.

The aural training modules that the author has so far thought it worthwhile to develop, are listed in Figure 3.4. The order in which the "Melody" and "Harmony" modules are listed in the figure reflect an increasing order in the number of concepts and skills involved. The interval discriminations that modules A and B are designed to teach, are included in those taught by module C. Modules A, B and C all require the student to remember the sounds
of two successive notes and identify the (pitch) interval between them. In addition to the above skills, Module D requires the student to remember the name of the first note and then, by identifying the interval, deduce the name of the second note. Module E increases the range of notes used in Module D. And even more note names must be deduced and more sounds remembered in modules F (4 notes per example) and G (6 or 7 notes per example).

MELODY

<table>
<thead>
<tr>
<th>Module</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>A 2 3</td>
<td>P4, A4, P5</td>
</tr>
<tr>
<td>B 2 4</td>
<td>m3, M3, m6, M6</td>
</tr>
<tr>
<td>C 2 11</td>
<td>m2 to M7</td>
</tr>
<tr>
<td>D 1 7</td>
<td>White notes from the octave</td>
</tr>
<tr>
<td>E 1 12</td>
<td>Black &amp; white notes above middle C</td>
</tr>
<tr>
<td>F 4 6 7</td>
<td>Dictation</td>
</tr>
</tbody>
</table>

HARMONY

<table>
<thead>
<tr>
<th>Module</th>
<th>Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>H 2 11</td>
<td>m2 to M7: Harmonic Intervals</td>
</tr>
<tr>
<td>I 3 3</td>
<td>M, m, A</td>
</tr>
<tr>
<td>J 3 6</td>
<td>M, m</td>
</tr>
<tr>
<td>K 3 10</td>
<td>M, m, A, D</td>
</tr>
<tr>
<td>L 8 9</td>
<td>I to I, IV, V &amp; inversions: Chord Progressions</td>
</tr>
<tr>
<td>M 9 4</td>
<td>(i) P, Pl, Im, I</td>
</tr>
<tr>
<td>N 20 4</td>
<td>(ii)</td>
</tr>
<tr>
<td>O 30 4</td>
<td>(iii)</td>
</tr>
<tr>
<td>P 60 6</td>
<td>(iv)</td>
</tr>
</tbody>
</table>

RHYTHM

<table>
<thead>
<tr>
<th>Time Signatures</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/4, 4/4, 6/8</td>
</tr>
</tbody>
</table>

FIGURE 3.4 Aural training modules. M=major, m=minor, A=augmented, D=diminished, P=perfect, Pl=plagal, In=interrupted, Im=imperfect. For the harmony test examples, * denotes the approximate number of notes in each, and the lower case Roman numerals imply the following: (i) two chords preceded by the tonic, (ii) a short melody precedes the cadence, (iii) begins in either major or minor mode, either modulating or not, (iv) modulation to one of 6 different degrees of the scale.

By working from Modules A and I through the alphabet, students gradually acquire new skills and concepts while reinforcing those that have just been learned (cf. student H in Section 3.5.1).
This cumulative approach is in agreement with the recommendations of educational psychologists (cf. Gagne, 1977, p.145). However, it is up to the teacher using the computerized aural trainer to decide what approach is taken and what musical examples are used.

Finally, in order to prepare the computer for use by aural students, the instructor (or computer operator) turns on sense switches A and B on the EAI 640 computer (see Section 3.3.1) and initialises the Musicianship Teaching Aid as explained in Section 3.3.2. The computer responds by asking what the student's name is, and the student responds in the manner outlined in the next section.
A training session begins when a student's name and a code number (which specifies the particular aural test module desired by the student) are entered at the console typewriter. A brief explanation of how the student should respond to the tests appears on the display screen. An example of such an explanation is shown in Figure 3.5.

HI THERE!!

AFTER HEARING EACH TEST, TYPE THE NUMBER YOU THINK DESCRIBES IT BEST, THEN PUSH THE BUTTON MARKED "RETURN".

(If you'd like to hear any test again, just push the "RETURN" button.)

GOOD LUCK!!

1 MAJOR - HAPPY
2 MINOR - SAD
3 AUGMENTED - WEIRD
4 DIMINISHED - DARK

FIGURE 3.5 A typical explanation of how the student should respond to the aural tests (for the aural training module set up as illustrated in Figure 3.3). The explanation appears on the screen before study commences. These instructions, down to the numbered categories, are the same for every module.

The student depresses one of the typewriter keys marked "RETURN" when ready for the tests to begin. The first test is then played by the computer on the organ, and the student may hear it over again any number of times, by depressing an appropriate typewriter key (identified on the screen). Next, the student identifies what seems to be the appropriate response to the test (i.e., what category it belongs to) by typing a particular number (also identified on the screen) - see Figure 3.5. The computer types either "GOOD" (and proceeds with the next test) or "HAVE ANOTHER TRY". In the latter case the test is replayed and another
response is awaited. If this new response is correct, "GOOD" is typed. Otherwise the computer types "NO! THE RIGHT ANSWER WAS X" (with X being the number and name identifying the correct category). The computer then types "HERE IT IS AGAIN", whereupon the test is replayed a final time. After a pause, the computer administers another test in the same way.

```
IKNAP RECOGNITION: TRY AND SING THE NOTES TO YOURSELF.

PLEASE PRESS 'RETURN' WHEN YOU'RE READY.
HERE WE GO THEN!!

AND WHAT WAS THAT?  3  GOOD!
AND WHAT WAS THAT?  1  GOOD!
AND WHAT WAS THAT?  2  GOOD!
AND WHAT WAS THAT?  3  HAVE ANOTHER TRY.
AND WHAT WAS THAT?  2  GOOD!
AND WHAT WAS THAT?  3  HAVE ANOTHER TRY.
AND WHAT WAS THAT?  1  GOOD!!
NO! THE RIGHT ANSWER WAS 2: MINOR - SAD

AND WHAT WAS THAT?  3  GOOD!
AND WHAT WAS THAT?  3  GOOD!
AND WHAT WAS THAT?  1  GOOD!
AND WHAT WAS THAT?  3  GOOD!
AND WHAT WAS THAT?  1  GOOD!
AND WHAT WAS THAT?  3  GOOD!
AND WHAT WAS THAT?  2  GOOD!
AND WHAT WAS THAT?  2  GOOD!
AND WHAT WAS THAT?  1  HAVE ANOTHER TRY.
AND WHAT WAS THAT?  3  GOOD!!
NO! THE RIGHT ANSWER WAS 2: MINOR - SAD

AND WHAT WAS THAT?  3  HAVE ANOTHER TRY.
AND WHAT WAS THAT?  2  GOOD!
AND WHAT WAS THAT?  1  HAVE ANOTHER TRY.
AND WHAT WAS THAT?  2  GOOD!
```

FIGURE 3.6 The computer printout for a brief aural training session. The student is learning to differentiate major, minor and augmented triads. As indicated by the increased rate of presentation of minor triads (category number 2), the interactive program is reacting to the student's weakness at recognising these. The student is requested to work at this weakness, by the program.
Initially, all categories have an equal probability of being presented to the student for identification. But the computer programs have been designed in such a way that after \( n \) incorrect responses have been made (where \( n \) is the number of different categories) the relative probabilities are altered so that those categories which were wrongly identified now have a greater likelihood of occurrence. After a further \( n \) mistakes are made the relative probabilities are adjusted again. This strategy concentrates the "teaching" on those categories that the student finds hardest to recognise. The computer programs have also been designed so that they continually order all of the student's difficulties, as reflected in the number of erroneous responses.

AND WHAT WAS THAT? 33

AND WHAT WAS THAT? 3 HAVE ANOTHER TRY.

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? 1 HAVE ANOTHER TRY.

AND WHAT WAS THAT? 32 EH ????

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? 1 HAVE ANOTHER TRY.

AND WHAT WAS THAT? 3 NO! THE RIGHT ANSWER WAS 2: MINOR - SAD HERE IT IS AGAIN...

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? 3 GOOD!

AND WHAT WAS THAT? 3 HAVE ANOTHER TRY.

AND WHAT WAS THAT? 1 NO! THE RIGHT ANSWER WAS 2: MINOR - SAD HERE IT IS AGAIN...

AND WHAT WAS THAT? 1 GOOD!

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? 1 GOOD!

AND WHAT WAS THAT? 3 GOOD!

AND WHAT WAS THAT? 2 GOOD!

AND WHAT WAS THAT? END

YOUR PERCENT SCORE FOR THIS TEST WAS 64

PLEASE WORK AT MINOR - SAD ( SEVERITY = 3 )

FIGURE 3.6 continued
In other words, the computer isolates the student's problems and arranges them in order of difficulty. Having done this, the programs then concentrate attention on the problem categories by increasing their rate of presentation proportionately. If subsequently during the training session the student's recognition of any of these particular categories improves, the emphasis is shifted by the programs to accommodate this improvement. In this way, each student's specific problems are continually reappraised during the administering of the aural tests. It would be well-nigh impossible for a human to take such care or show so much patience.

At any time the student may request a replay of the current test example. By typing "END" as a response, the module may be terminated, at which juncture the computer prints out the student's point score for the module together with an indication of those categories that caused the most difficulty during the training session. After noting this, the student may select another module for study, or move over for the next student. An example of the computer printout from a typical training session is illustrated in Figure 3.6.
3.4. ASPECTS OF LEARNING - THEORY INVOLVED IN THE DESIGN OF THE COMPUTERIZED AURAL TRAINER.

Consider again the giving of aural training using traditional techniques. Human teachers, as well as giving encouragement, also provide clues and helpful suggestions in the form of either external strategy suggestions such as "Listen to the bass line", or mnemonic-type suggestions of the "interval - familiar tune" variety described in Section 3.2. With computerized training, the former suggestions can be printed out at the beginning of the module, while the latter can be displayed on the screen next to the category to which they refer, and remain before the student throughout the training session, as explained in Section 3.3.4. Limited encouragement is given by the computer typing "GOOD" when the correct response is made. This immediate assessment also provides augmented feedback, which has been shown to have lasting, beneficial effects (cf. Smode, 1958). (Feedback is explained in Section 6.4.2.2.)

The most rudimentary strategy for administering multiple-choice aural tests consists perhaps of the repetition of the two steps: (1) administer a new stimulus, (2) assess the student's response. Hullfish (1972) has shown that computerized aural training is made more efficient if the choice of stimulus is based on the student's previous responses. Moreover, if at the first attempt an incorrect response is made, the student should be given a second chance, and should always be informed of the correct response before another test is presented. This facilitates the formation and testing of hypotheses essential to the process of concept formation (cf. Fitts and Posner, 1967). Finally, Killam et al (1975) have shown that, within a single aural test module, certain categories of stimuli can be more difficult to identify than others. The experimental results presented in Section 3.5.1 confirm this and show, in addition, that these categories tend to vary, not only from person to person, but also from day to day. To take proper account of this would require increasing the frequency of presentation of the more difficult categories. This biasing could be based on statistical tests over a sufficiently large population, since general trends have been shown to exist for certain aural tests (see Killam et al, 1975). Ideally though, biasing should be interactive, taking into account the difficulties experienced by individual students and adapting to their progress during the course of the training. Taking all these points into consideration, the author has adopted the strategy summarized in Figure 3.7, in which all the desirable features discussed above are incorporated. Augmented feedback is provided by printing an assessment of the student's performance at the end of the module together with a suitably ordered list of those categories over which most difficulty was experienced. Hypothesis formation and testing are aided by the unlimited number of replays available, the immediate assessment of the student's responses, and by the repetition of a test example after the printing of the correct answer when the student twice fails to identify the required category. As a result of the interactive biasing, the choice of stimulus is dependent on the student's previous responses, with the more recent having
greatest influence.

In the above ways, the computerized aural trainer is seen to possess qualities that music educators and psychologists consider desirable.

FIGURE 3.7 Flow diagram summarizing the way the computer programs administer tests from an aural test module.
3.5. EXPERIMENTAL RESULTS.

3.5.1. REGULAR UNDERGRADUATE USERS

After the preceding theoretical discussion, this section reports on the practical evaluation of the computerized aural training system described in Section 3.3. First, the results obtained from training three music students (identified by the initials of their first names: H, T and M) are examined.

![Graph](attachment:image.png)

**FIGURE 3.8** H's point scores, as recorded by the computer at each training session, for those aural tests with which she had difficulty before working with our system (the upper case letters on the graph refer to the modules listed in Figure 3.4).

The three students enrolled in the course AURAL I at the University of Canterbury at the beginning of 1976. A pass in this three-semester course requires 50 points out of a possible 100, made up of 20 points each for tests set at the ends of the first two semesters and 60 points for the end-of-year examination.

All three students experienced difficulty with aural training. The first student, H, who works as a physiotherapist as well as being a semi-professional double-bass player, failed her first semester test, gaining only 7 points. She then began remedial
tuition for an average of two and a half hours per week with the computerized aural trainer. Both her confidence and her competence increased steadily (see Figure 3.8) and she gained 15 points in her second semester test. In the end-of-year examination she passed comfortably. When commenting on her experience with computerized aural training, she writes: "The isolation of, and concentration on, the student's weak areas by the computer is one of the most important aspects of the program and leads to intelligent practice at home, hopefully resulting in mastery over that particular problem!... You can work more efficiently and with greater concentration with the impersonal computer than with another person."

Before commencing music studies at the University of Canterbury in 1975 T had had no formal musical training. He now studies piano and flute, and in 1976 attended AURAL I lectures out of interest only (he did not register for the examination). From the start of the AURAL course he experienced difficulty with the work. During 1976 he received aural training from the computerized aural trainer for an average of two and a half hours per week, starting two weeks before the end of the first semester. After ten training sessions a disturbing trend emerged (see Figure 3.9). Aural skills relating to melody were improving steadily, but T was having difficulty with the harmony tests, and his performance was actually worsening with the "simple modulation" tests (see the curve marked O in Figure 3.9).

![FIGURE 3.9 T's point scores, as recorded by the computer at each training session, for harmony and melody tests (the upper case letters on the graph refer to the modules listed in Figure 3.4). The improvement in the melody point scores (A,C,D) is immediate. The harmony point scores (M,J,O) are disappointing at first (sessions number 1 to 21) but improve later, as is explained in the text.](image-url)
This remained mystifying until we discovered that T found it difficult to identify harmonic intervals of notes sounded together, something that is a comparatively easy task for most musicians. We then designed an experimental test for him. He was played randomly chosen melodic intervals (i.e. the notes were played sequentially) for identification. Each example was played twice before he responded, and there were no extra replays or second attempts allowed. He was then given a similar test involving harmonic intervals. He scored 100 points out of 100 for the melodic test, but only 33 out of 100 for the harmonic test! This confirmed our suspicions. Accordingly, a special test module for teaching harmonic intervals was designed. After working for a month with our system, concentrating solely on harmonic interval recognition, T began to overcome his problem. His point scores for modules H, J, and K, for training sessions number 23 to 43, show his steady improvement (see Figure 3.9).

T comments: "It is very important that the student comes well prepared for his computerized training session. That is, he should be alert, and rested both in mind and body. Also, he should have 'warmed up' beforehand by playing similar material on the piano... I find the computer an excellent adjunct to the other means at my disposal to train my musical hearing because it has teaching as opposed to testing built into its inscrutable (stimulus) selection process. What the computer does is reinforce the more mechanical aspects of teaching - and presumably makes what remains between teacher and student so much more profitable and creative."

M is a viola and timpani player with semi-professional orchestral experience. She enrolled at the University of Canterbury in 1976 for a Diploma of Music in Viola performance, and must pass AURAL I and AURAL II to obtain this qualification. After experiencing initial difficulties with the AURAL I course work she enlisted the help of a friend to give her extra practice and advice for about an hour per week. In spite of this, M scored only 3 points out of 20 for her second semester test, having failed, but less dismally (7 points), in the first semester test. Her aural instructor told her that she was likely to fail AURAL I in 1976. At the end of the second semester she undertook a "crash course" using the computerized aural trainer, taking six training sessions per week for 5 weeks. After initial rapid progress in the aural training modules, her rate of improvement eased off. A detailed scrutiny of the computer's record of her training sessions revealed certain trends: major and minor sixths and sevenths accounted for most of the melodic interval recognition difficulties, whereas diminished triads and their inversions, together with augmented triads, caused the most problems in the recognition of all the triads and their inversions. Accordingly, special modules were designed to deal with these deficiencies, and when she started training with these there was an immediate improvement in her recognition of melodic intervals and of triads and their inversions. In order to be credited with a pass in AURAL I, M required a minimum of 67 percent in the end of year examination (to make up for the low number of points she had
obtained in the semester tests). She was not able to reach this standard in 1976 in the five weeks she spent with the computer, but her confidence and grasp of the basics increased considerably, and she subsequently passed the AURAL I course in 1977. In December, 1976, she observed: "I hear intervals much more clearly now, which lets me tune timpani much faster and more accurately than before I came to the computer... I don't mind doing badly so much with the computer - it never gets annoyed, and it's very helpful being told exactly what to practise at home... Unlike in university lectures, I am grateful for the individual attention my problems receive, and the hammering home of the basics."

Although the results of H, M and T's training sessions differed in many ways, one common feature did emerge: a particular person's problem areas always changed in emphasis or content from one training session to the next, and often within a single training session. It is important that future attempts at aural training by computer should take this into consideration. This phenomenon is possibly due to hypothesis formulation and testing, during concept formation (cf. Bruner et al, 1962) over a period of several training sessions.

Something that strongly impressed the author during the training of H, M and T was that the modular nature of the computerized aural training system makes it easy to single out specific skills for special attention. By keeping a record of a student's special problems during each training session, individual deficiencies can be detected, and remedial modules designed accordingly. M's two remedial modules took less than half an hour to create, and it is worth remembering that these can be used for other students experiencing similar difficulties.

3.5.2. A CAUTIONARY TALE.

To conclude the account of the experimental use of the computerized aural trainer, the results of two irregular users (identified by the initials of their first names: E and R) are now described. These results show the importance of following a logically structured aural training course. They also indicate that teaching by computer is a two-way process - it can only succeed with the student's active co-operation. The computer cannot be expected to work wonders by itself.

E had received no formal aural instruction before coming to learn from the computerized aural trainer. She wanted to become proficient in the most difficult tests stored in the system (e.g. Module P - see Figure 3.4) in order to pass an examination (L.T.C.L.) which would give her a clarinet-teaching qualification. In mid-1977, she began studying with the computer, without musical supervision, choosing only the modules that interested her. After three training sessions, E became very frustrated as she felt that she was not making any progress at all either in terms of her own understanding or in terms of her point scores obtained with the computerized aural trainer. The author then
pointed out to E that the aural training modules are carefully arranged in a hierarchy of accumulating concepts and skills, and that there is little point in trying to work at an advanced module (e.g., module N or P, of Figure 4) before the concepts dealt with by the more elementary modules have been properly learned. The contents of the modules and their position in the hierarchy were explained, and the author planned and supervised E's study for the next few lessons. She then resumed control over her aural studies with the computer as she felt more confident and was making steady progress at last.

R, a technical officer, had been learning the piano for less than a year when he expressed interest in receiving aural instruction from the computer. After an explanation of what is involved, he was started off on modules A, B and I (explained in Figure 3.4), receiving on average about one lesson with the computerized aural trainer per fortnight. After R had received five computerized lessons, the author noticed that R's score and extra work prescribed for module B (by the computerized aural trainer) were virtually identical for lessons 3, 4 and 5. When confronted with this evidence, R cheerfully admitted to having done no aural practice in between computerized lessons - he expected the computer to (magically?) teach him without any special effort being required on his part! Needless to say, R's results improved when he began practising aural exercises at home again.

The above two examples respectively highlight the dangers of unsupervised, unstructured aural training, and show that computerized instruction is not a substitute for conscientious work! Contrary to popular misconceptions, the computer does not possess magical properties, a fact that some students may need to be reminded of.
3.6. SUGGESTIONS FOR FUTURE RESEARCH

As explained in Section 3.2.1, all the aural tests listed in Table 3.1 not involving singing, clapping or beating time can be taught by computer. Section 3.3 describes a computerized aural trainer which can be used for this purpose. Methods for extending this trainer to include singing and tapping responses are now described.

FIGURE 3.10 Melodic dictation using the computer. At * the student types "R" and plays the melody he has notated, on the organ keyboard for assessment. (Everything else is typed or played by the computer). At the student presses the "ENTER" button to hear the music again. His mistakes (marked X by the author) are clearly indicated by the computer's typed comments.
Tucker (1977) describes a method by which notes that are sung or hummed are input directly to the programs. The musician sings (or hums) into a condenser microphone which is interfaced to the computer. At the same time, inside the computer, a pitch estimation algorithm (developed by Tucker and Bates, 1977, 1978) is used to determine the notes that are being performed. In this way, the human voice can be used as an input to the Musicianship teaching aid described in Section 3.3.2. A system which, for a single, performed (audio) note input, outputs a numerical estimate of the pitch is here referred to as a "pitch estimator" (such a system has been developed by Tucker, 1977, pp.208 and 372-387).

Figure 3.4 lists the aural training modules that the author has so far thought it worthwhile to develop. A recent addition is melodic dictation, in which the student notates a melody played by the computer programs and then plays it back on the organ. Any mistakes are immediately identified on the typewriter, as is shown in Figure 3.10. The incorporation of Tucker’s (1977) pitch estimator (described above) into the computerized aural trainer would enable students to sing responses to aural tests. Thus, the vocal imitation of a computer-played melody might well be assessed in exactly the same manner as melodic dictation is assessed (see Figure 3.10). However, as pointed out in Section 3.2, the assessment of singing and rhythm tests requires a certain amount of interpretation by the instructor. In the author’s teaching experience, students are likely to omit or add notes when trying to sing a melody that has been played for them to imitate. They may also slow down in the difficult parts, drift off the correct pitch, or reproduce only part of the melody correctly. Programs would need to be designed to recognise the above errors and take appropriate action e.g. slow down the replay for the student’s next attempt, or only replay the incorrectly sung parts.

A push-button switch has been incorporated in the computer system by Tucker (1977) for entering barline information while recording music on the organ keyboard. It is perfectly feasible to design programs which allow students to respond to rhythm tests on this button (or on a note of the organ keyboard) instead of by the usual clapping. Beating time could be replaced by the pressing of several such buttons (or six specially designated keys on the organ keyboard) numbered from 1 to 6, say. The student would tap each beat on the correspondingly numbered button (or note). As with the melody tests mentioned above, programs would need to be designed to recognize common errors in rhythm and time-beating (e.g. omitting a note or beat) and take appropriate action (e.g. pointing out the mistake to the student and replaying all or part of the test for another attempt).
3.7. CONCLUSIONS

The computerized aural training system described in this chapter seems to possess most of the features that one would ideally like it to have. It is easy to use, both for student and instructor. It adapts, in a very real sense, to the changing needs of students. As shown in Section 3.5.1 the modular nature of the aural training system makes it easy to single out specific skills for special attention. Experimental results (reported in Section 3.5) indicate that students' aural difficulties vary appreciably from person to person, and change with time. The author's experience (cf. Section 3.5.1) suggests that the computerized aural trainer is not merely a substitute for a human teacher: in many ways it is better than a human teacher, because it does not introduce any emotive stress (e.g. a computer never loses its temper!) However, of critical importance are the design and organization of the aural training modules, which of course depend upon the creativity and judgment of the associated music teachers.

The acceptance by musicians of the computerized aural trainer is indicated by its use for remedial aural training by the Music Department of the University of Canterbury.
4. COMPUTER AIDED HARMONY ASSESSMENT

4.1. INTRODUCTION

An important branch of music theory instruction is the teaching of 4-part harmony. This involves the analysis and composition of music in four parts (SATB i.e. soprano, alto, tenor, bass) in the style that J.S. Bach used in his 371 chorales (cf. Riemenschneider, 1941). Its relevance to contemporary music is indicated by the existence of harmony texts by such noted twentieth century composers as Hindemith (1942), Schoenberg (1954), and Piston (1949). Also, an internationally recognized training course in music theory currently includes four part harmonization in its syllabus (cf. T.C.L., 1977, pp.47-48) as do the music degrees offered by the University of Canterbury (cf. U.C., 1978).

The teaching of four part harmony usually begins with an explanation of the basic concepts (e.g. inversion and root of a chord). Appropriate musical illustrations are given, and the student is set exercises embodying these concepts. In general, these exercises can be divided into the "predominantly mechanical" (e.g. harmonization of a cadence) and the "predominantly creative" (e.g. composition of a melody above a given bass). Assessment of students' work in the former ("mechanical") category is often tedious and time-consuming and, where large classes are involved, can dissipate much of the instructor's creative energies. In an attempt to reduce this tedium, the author has developed computer programs which assess a student's harmonization for violations of standard "harmony rules" and for certain stylistic features of a "mechanical" nature. In addition, the programs produce a harmonic analysis of the student's work, and provide an alternative harmonization based on the student's version when any error or stylistic irregularity is detected. The resulting computer printout is referred to as a "computer assessment", a typical example of which is shown in Figure 4.1. It is then left to the instructor to make any changes or extra comments considered necessary, before giving the assessment to the student.

To date, most of the examples of computer aided instruction (C.A.I.) in musicianship have been concerned with composition, performance techniques, aural training, and elementary music theory (as outlined in Chapter 2). The author has not been able to find any published account of C.A.I. in more advanced aspects of traditional music theory in general, or in four part harmony in particular. Therefore, the computerized aid described here can be said to extend the range of C.A.I. systems currently available to music educators.
THE HARMONIZATION BEING ASSESSED IS...

D - D'  F - F'  E - C  B -
D' - G  B - C'  C - C'  D -
F  B - F  A - A - F  F -
B - G, B - F, C A B -
I VI I V II VI I

*******************************************************************************
# CHORD 2 TO CHORD 3#
*******************************************************************************

ROOTS AWKWARDLY RISE A THIRD, WEAK TO STRONG!
RATHER A BUMPY EXPOSED FIFTH, DON'T YOU THINK?
THERE ARE EVIL PARALLEL FIFTHS BETWEEN SOPRANO AND BASS!

*******************************************************************************
# CHORD 3 TO CHORD 4#
*******************************************************************************

THERE IS MORE THAN AN OCTAVE BETWEEN THE SOPRANO AND THE ALTO.

*******************************************************************************
# CHORD 4 TO CHORD 5#
*******************************************************************************

LEADING NOTE DOES NOT RESOLVE.
THERE IS MORE THAN AN OCTAVE BETWEEN THE SOPRANO AND THE ALTO.
THERE IS AN ILLEGAL LEAP IN THE TENOR!!

*******************************************************************************
# CHORD 5 TO CHORD 6#
*******************************************************************************

THERE IS MORE THAN AN OCTAVE BETWEEN THE SOPRANO AND THE ALTO.
THE THIRD OF THE CHORD IS RATHER LOW.

*******************************************************************************
TRY TO GET THE TENOR PART A LITTLE HIGHER IN FUTURE.
NOT GOOD ENOUGH, I'M AFRAID!

HERE IS AN ALTERNATIVE HARMONISATION:

D - D'  F - F'  E - C  B -
D' - G  B - C'  C - C'  D -
F  B - C  D - E'  F  D -
B - G, F, F, G, A B -
I VI I V II VI I

FIGURE 4.1 A "Computer Assessment" of a student's harmonization identifies common errors and suggests an alternative version which does not contain those errors. (The musical notation has been added using the "music typewriter" program)
The next section discusses those aspects of harmonization that are covered by the author's system for aiding harmony assessment. Then, the analysis programs are outlined, in Section 4.3, showing how cues in the music are used to resolve ambiguities. This is followed by a description of the way in which "computer assessments" are obtained.

Experiments with two undergraduate harmony classes are described in Section 4.5. Finally, the computerized system is evaluated in the light of results from these experiments. Throughout this chapter the term "harmonize" refers to four part harmonization (SATB).

4.2. STYLISTIC CONVENTIONS IN FOUR PART HARMONY

When harmonizing, the student must obey a number of restrictions based on the physical limitations of the human voice and on the musical conventions established in Bach's era. These restrictions are summarized in Table 4.1. In addition, the student must be aware of certain stylistic features (e.g. parallel fifths) which occur very rarely in Bach's music and which, if used indiscriminately, would be quite out of keeping with Bach's style. Table 4.2 summarizes those features considered by Lovelock (1947) to be undesirable in elementary student harmonizations (Lovelock forbids the use of features (1) and 1-6 of Table 4.2 in any harmonization). To start with, students are usually encouraged to harmonize in a manner that avoids the use of the features listed in Table 4.2. As their command of harmony improves they gradually learn to recognize the circumstances in which some of these features may be acceptable (e.g. features 8-14 of Table 4.2 are quite acceptable when they occur as a result of interesting melodies in the voices).

When assessing a student's harmonization, the instructor must discriminate between two contrasting uses of stylistic features of the type contained in Table 4.2. On the one hand there is the inept student unfamiliar with Bach's style - on the other, there is the imaginative student experimenting with original ideas. Students of the "inept" category need the reasons for their unstylistic harmonizations pointed out, together with constructive suggestions for avoiding similar improprieties in the future. Students of the "imaginative" category should not be criticized if their work is almost in keeping with Bach's style. Instead, their use of any feature from Table 4.2, whether intuitive or calculated, should be pointed out, in order to sharpen their awareness of their use of that particular stylistic feature. Since it is difficult (or impossible?) to program a computer to recognise these two types of student, the programs described in the following sections are not designed to make this kind of discrimination. Instead, it has been arranged that the computer programs print a critical message whenever any of the restrictions listed in Table 4.1 is violated or when any of the worse features from Table 4.2 occurs. These worse features,
numbered (1) to (8) and (i) to (iv), are henceforth referred to as "non-permissible features". The occurrence of any of the remaining features of Table 4.2 is indicated by an uncritical typed message. Whenever a violation or "non-permissible feature" is detected by the programs, the melody is reharmonized (by the programs) so as to eliminate its recurrence. This new harmonization is based on the student's work by incorporating as much as possible of the latter up to the first violation or non-permissible feature. Thus, the "inept" beginner has his mistakes explained and corrected, while the "imaginative experimenter" who doesn't use any non-permissible features has those stylistic features that might be considered unacceptable in other circumstances, pointed out. Finally, it is left to the instructor to add any admonishing or encouraging comments considered necessary.

PHYSICAL RESTRICTIONS

The four voices must lie within prescribed pitch ranges.

A voice may not leap an augmented interval or a major seventh; or any interval larger than an octave, even with one note intervening.

Vocal leaps of a diminished fourth and diminished seventh are discouraged.

GENERAL MUSICAL RESTRICTIONS

The music is restricted to discrete pitches of the great stave, and must be tonal, or (occasionally) modal.+

The only essential chords permitted are the following complete chords: major, minor, diminished, augmented, dominant seventh; together with the following incomplete chords (i.e. the fifth of the chord is absent): major, minor, dominant seventh.

All first and second inversions of major and minor chords must be complete.

TABLE 4.1 Restrictions which students should obey when harmonizing. All (except for the restriction marked "+") are tested for by the computer programs and any infringements are indicated in the computer assessment.
"UNDESIRABLE" STYLISTIC FEATURES

FOR VOICES:

1. Parallel fifths or parallel octaves.
2. Exposed fifths or exposed octaves (except between chords with the same root or in the progression II-V).
3. A doubled leading note.
4. An incorrectly resolved dominant seventh chord.
5. A diminished fifth leap which is followed by a note outside its compass.
6. An octave leap which is not preceded and followed by notes within its compass.
7. A leading note in a minor scale which is not raised.
8. Similar motion in all voices between chords with different roots.
9. A leading note which falls (except in a descending scale passage, or in a perfect cadence in which it falls a major third).
10. Any chord that is not a first inversion, in which the third of the chord is lower than the F sharp below middle C.
11a. Soprano and alto parts that are separated by more than an octave.
11b. Alto and tenor parts that are separated by more than an octave.
12. Voices that overlap by more than one semitone (except between chords with the same root).
13. Crossed parts.

TABLE 4.2
FOR CHORDS:

(i)* An ending that is not a Perfect, Plagal or Elliptic cadence.

(ii)* The progressions II-I, VIIB-V, VIIB-IV, VIIB-IVB.

(iii)* Roots that rise a third, weak to strong.

(iv)* A chord that is repeated weak to strong with the same melody note.

(v)* A second inversion that is neither cadential nor passing.

FOR THE OVERALL HARMONIZATION:

(a) The inner parts move disjointedly i.e. the average leap in the alto and tenor parts is greater than three semitones.

(b) The average pitch of the tenor is lower than the A below middle C.

Table 4.2 (continued)

A summary of the stylistic features which Lovelock (1947) considers undesirable in harmonizations by beginner harmony students. The features that are least characteristic of Bach's chorales are listed first in each group. Those that are marked with an asterisk are referred to in the text as "non-permissible features".

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In order to assess a harmonization in the manner just described, the following information is required: the key of the harmonization, and the root pitch, chord-type and inversion of every chord. The author has developed analysis programs to deduce the above details using only the pitches and timing information which have been inputted (as outlined in Section 4.4). Because it requires a certain amount of musical training for a person to deduce the key and the root pitches, the programs which do so can be said to exhibit a form of Artificial Intelligence.

The key-analysis program improves Longuet-Higgins and Steedman's (1971) algorithm for deducing the key from the note names, by in addition using musical cues to resolve ambiguities. The following section explains how this is done, and it is shown how the improved algorithm is extended to deal with modulations.

Because the programs that analyse the chord type, root pitch and inversion of a chord are essentially mechanical in nature, they are merely summarized here. A more detailed description of their operation is given in Appendix 1.

The analysis procedure begins by transforming each chord into its "close" form in root position (this transformation is described in Appendix 1). Then, its type is found by comparing the transformed chord with standard chords in root position (this method of comparison is similar to that used by Hofstetter, 1972). The original chord's type is the same as that of the corresponding standard chord (i.e. the one that matches the transformed chord). Next, the inversion of the original chord is found by comparing its Bass note with the notes of the corresponding standard chord. The root pitch is obtained by using one of the two following methods. Either it is determined when the standard chord is matched, or, if a match does not occur, the root pitch is estimated using a technique developed by the author. The method of estimation (described in Appendix 1) is independent of note names (e.g. B sharp is treated the same as C). Such an algorithm is needed because only pitches and timing information are available from the music that is inputted in the manner described in Section 4.4.

The root pitch information obtained in the above manner is used by the key-analysis program as is explained in the following section. The analysis of the student's work concludes when all the details that have been deduced by the programs (as outlined above) are combined to produce a chordal analysis of the harmonization. Section 4.3.2 describes the implementation of this final stage.
4.3.1. FINDING THE KEY

The program for key analysis uses a pitch class (cf. Forte, 1973) derived from the notes of the harmonization. This pitch class is compared with standard major and minor scales, in order to find the keys to which the music can belong. Root pitch leaps and voice-leading cues in the melody are used to resolve ambiguities. The way in which all this is done is now explained.

<table>
<thead>
<tr>
<th>CUE</th>
<th>IMPLIED TONALITY</th>
<th>&quot;WEIGHT&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Keynote</td>
<td>Mode</td>
</tr>
<tr>
<td>Semitone leap</td>
<td>the second note</td>
<td>major &amp; minor</td>
</tr>
<tr>
<td>Perfect 4th upwards or perfect 5th downwards leap</td>
<td>the second note</td>
<td>major &amp; minor</td>
</tr>
<tr>
<td>Semitone leap downwards</td>
<td>major third below the second note</td>
<td>major</td>
</tr>
<tr>
<td>Semitone leap downwards</td>
<td>perfect 4th above the second note</td>
<td>minor</td>
</tr>
<tr>
<td>First note of the melody</td>
<td>the first note</td>
<td>major &amp; minor</td>
</tr>
<tr>
<td>Perfect 4th upwards or perfect 5th downwards leap*</td>
<td>the second note</td>
<td>major &amp; minor</td>
</tr>
</tbody>
</table>

Table 4.3 Root pitch and soprano voice leading cues used for finding the key e.g. F followed by E, in the melody, suggests that either C major or A minor is the key. (* denotes a root pitch cue - all other cues are melody cues.)

During the analysis, each major and minor key is assigned a "bias value", which is initially set to 1. The procedure starts with the formation of a pitch class comprising the soprano note of the first chord. This pitch class is then compared with (the pitch class of) each major and harmonic minor scale. The scales to which this first note cannot belong are then "eliminated" by having their bias values set to zero (keys with a non-zero bias value are referred to as "possible").
Next, the alto of the first chord is added to the pitch class, and the above "elimination step" is repeated (the term "elimination step" here refers to the comparison of the pitch class with all the scales, and the elimination of those scales to which it cannot belong). The tenor and bass notes of the first chord are then added to the pitch class, followed by the soprano, alto, tenor and bass notes of the second chord, and so on. An elimination step takes place as each note is added.

During the above process of key elimination and pitch class enlargement, the program examines the harmonization for the voice leading and root pitch cues listed in Table 4.3 (note the "weight" assigned to each cue). Whenever one of these cues is found, the bias value of the "implied key" (see Table 4.3) is incremented by the weight assigned to that cue. Bias values of zero are not incremented (the weights reflect the relevance of the cues to the key, in the author's opinion). The parallel processes of cue searching and key-elimination continue until (a) every bias value is set to zero, or (b) the end of the harmonization is reached. In the latter case, the key of the harmonization is taken to be the one with the highest bias value at the end of the piece. Case (a) may occur if the student (whose harmonization is being assessed) makes a mistake or uses a chromatic chord, modulation, chromatic unessential note or the melodic minor scale. Accordingly the following procedure has been developed to take account of such occurrences.

Whenever the addition of a new note into the pitch class causes all bias values to be set to zero (i.e. all keys are eliminated) the program discards note(s) from the pitch class so that at least one key becomes possible. It is arranged that the new note is retained in the pitch class, and that the smallest number of pitches is discarded as is needed to enable the resulting pitch class to belong to at least one scale. It is also arranged that the more outdated pitches tend to be discarded first.

The program then continues searching for cues and eliminating keys as before. Whenever the bias values all become zero, notes are discarded again from the pitch class in the manner just described. Thus there is always a possible key defined at each point in the harmonization. Wherever any notes are discarded from the pitch class, a marker is set by the program. This marker is used (by the program) when analysing modulations, as is explained next.
4.3.1.1. IDENTIFYING MODULATIONS

"Modulation may be familiarly defined as a method of key-change without pain" (Scholes, 1950, p 589). It is characterized by a cadence (usually some form of perfect cadence) in the new key and by the use of at least one note which belongs to the new key but not to the old (cf. Lovelock, 1947, p. 76). The markers set by the programs, as described in Section 4.3.1, indicate places where notes belonging to new keys occur. To determine whether a modulation has actually taken place, the program searches the section of the harmonization between that marker and the next for a root pitch progression of V-I, in the key with the highest bias value just before the next marker (or end of the harmonization). If such a progression (which includes all forms of perfect cadence) occurs, that section of the harmonization is taken as being in this key (a perfect cadence is called an "authentic cadence" in U.S. terminology). The program is arranged so that modulation is not considered to have occurred if the section (bounded by markers) contains only two chords and the preceding and following sections are in the same key. Nor are Tières de Picardie treated as modulations by the program.

In the above way the programs do not treat chromatic chords, chromatic unessential notes, or errors of notation as being modulatory by themselves. (This is in agreement with the general principles of harmony.)

Longuet-Higgins and Steedman's (1971) algorithm for key-identification positions the notes (of the music) on a two-dimensional matrix. Keys to which the notes cannot belong are eliminated - the algorithm is not designed to deal with modulations. Nor are musical cues used, except to regard the first melody note as a possible dominant or tonic.

4.3.2. NAMING THE CHORDS

The programs combine the information about the key, root pitches, inversions and chord types (obtained in the manner described in Section 4.3.1 and Appendix 1) to produce a chordal analysis of the harmonization. This is output in the standard notation (a Roman numeral indicates root pitch with respect to key e.g. "I" indicates a root pitch which is the first note of the scale; the inversion of the chord is denoted by a letter e.g. "B" denotes a first inversion, "C" a second inversion, and so on; and a "7" shows that the chord is a seventh). Figure 4.1 contains a typical chordal analysis of a harmonization which does not modulate. In Figure 4.2, the programs' analysis of Bach's Chorale number 130 (cf. Riemenschneider, 1941, p.29) is displayed underneath the musical notation. This harmonization's frequent modulations between E minor and G major are correctly identified by the programs. However, some musicians would say that the final modulation occurs one chord earlier than the programs indicate (i.e. at the E minor chord at the beginning of the penultimate bar). Others might say it occurs a further chord earlier (i.e. it
can be argued that the antepenultimate bar shown in Figure 4.2 contains the "pivot", or modulating, chord - IIB in G major functioning as IVB in E minor). This illustrates a weakness of the programs - the choice of the pivot chord in a gradual modulation (which is something that musicians are not always in agreement about). Because the programs are designed to indicate that modulation occurs at a "marker" (i.e. when a new note occurs), they usually identify abrupt modulations correctly, whereas gradual modulations tend to be indicated after they occur.

A better estimate of the pivot chord (cf. Winograd, 1968, p 37) would be obtained by using a tonal centre, calculated from root pitch progressions, to determine the change in key.

Insofar as they do not deal with voice leading, the harmony analysis programs described in this thesis lack the musical sophistication of the computerized methods of Jackson (1967) or Winograd (1968). However, these authors' methods both receive as input the key signature and note names (via an alphanumeric code), which contain much more information than do the pitches which are inputted to the analysis programs described here.
4.4. OPERATION OF THE COMPUTERIZED ASSESSMENT AID

The procedure for harmony assessment begins when the command "R" is typed on the console typewriter (the layout and operation of the computerized musicianship aid are described in Section 3.3). Next, the harmonization to be assessed is played on the organ keyboard. The subsequent typing of "S" causes the musical notation for what has just been played to appear on the display screen. Any mistakes in the playing are corrected by electronically "pointing" to them and then playing the desired notes on the organ keyboard. This editing process, which is outlined in Section 3.3.3, is described in detail by Tucker (1977). Such mistakes may be due to carelessness in playing, or because the notes of the harmonization, although singable, may not be within the span of the hands on the keyboard (the latter is the case with the harmonization shown in Figure 4.1).

Next, "M" is typed. This activates programs which analyse the harmonization with regard to root pitch, key and chord-type (these analysis programs are outlined in Section 4.3 and described in detail in Appendix 1). The name of the student whose work is being assessed is entered on the console typewriter, after which the programs output a "computer assessment". This comprises the following:

1. the name of the student;
2. the harmonization being assessed (notated alphanumerically - as in Figure 4.1);
3. a chordal analysis of the harmonization;
4. a list of any rule violations and "undesirable" stylistic features that occur (as explained in Section 4.2);
5. a general comment expressing either disapproval or encouragement; and
6. an alternative harmonization based on the student's work but without any of the deficiencies listed in (4). This alternative harmonization is only included in the assessment if the student's work is found to contain "non-permissible" features (these are described in Section 4.2).

With an experienced operator, the procedure described above takes approximately one minute for an 8 chord harmonization. If desired, the alternative harmonization may be played back by the programs (upon the command "P" being typed). It may also be displayed in traditional notation, using the "music typewriter" programs developed by Tucker (1977).

In the above way the computer is used to assess students' harmonizations in a manner which is quick and easy for the operator. Very little prior knowledge of computers is needed in order to use the system.
4.5. EXPERIMENTAL RESULTS

This section presents an account of two experiments in which computer programs were used to assist the teaching of harmony. The first experiment took place at a time when the assessment programs (outlined in Sections 4.2 to 4.4) and the harmonizing programs (described in Chapter 5) were still being developed. Undergraduate harmony students critically discussed the programs' assessment of their work. Also, the musical shortcomings of program-produced harmonizations were used to show that the slavish adherence to a set of rules does not in itself guarantee a musically acceptable result.

In between experiments, critical suggestions made by the students and their tutor in the first experiment were taken into account in a considerable upgrading of the assessment and harmonizing programs.

The second experiment took place when the assessment system described in Sections 4.2 to 4.4 had been virtually completed. This experiment demonstrates the manner in which the computer programs meticulously detect violations of restrictions listed in Table 4.1 and identify stylistic features (from Table 4.2) occurring in student harmonizations. Harmony "errors" are corrected acceptably, for the most part, by the programs in the manner described in Section 4.2. The experiment shows that student harmonizations can be assessed with the aid of a computer, in a classroom situation.

4.5.1. EXPERIMENT 1 - DEVELOPMENT

METHOD: Between April and June, 1975, prototype computer programs for assessing four part harmony were developed and tested with the co-operation of an undergraduate harmony class at the University of Canterbury. During the period of the experiment the class tutor, a Senior Lecturer (i.e."Associate Professor", in U.S. terminology) in the School of Music, divided the classwork into "mechanical" and "creative" categories. On four occasions a selection of student harmonizations from the "mechanical" category was assessed by computer programs for rule violations and "undesirable" stylistic features of the type contained in Tables 4.1 and 4.2. Then, the computer printout, comprising a detailed list of violations and stylistic features for each student harmonization (not including an analysis or alternative harmonization) was discussed in class, and critically evaluated in private by the tutor. The computer programs were subsequently changed so as to accommodate the criticisms and recommendations made. The amended programs were then used to assess the next collection of student harmonizations, providing the basis for a further round of discussion, evaluation, and upgrading of the computer programs.

Towards the end of the experiment, every member of the class sat an examination which included an exercise in four part harmony. Each student's examination paper was assessed by the tutor who
then sent the harmony exercises over to be assessed again, this time by the computer programs. The two independent assessments of each harmony exercise were then compared.

On three occasions the class was shown examples of four part harmony produced by early versions of the harmonization programs described in Chapter 5. The good and bad points of these examples were discussed by the class in the light of the harmony "rules" formulated by Lovelock (1947).

All students in the class participated in the experiment, which was incorporated into their normal work.

RESULTS: Students were interested in the programs' criticisms of their harmonizations, although they did not always agree that the features indicated by the programs were inapt in the particular musical context. These disagreements led to stimulating class discussions on the need for flexibility in the interpretation of the harmony "rules" (e.g. the rule forbidding exposed fifths and exposed octaves should be modified to allow an exposed fifth between chords II and V where it sounds quite acceptable - cf. Lovelock, 1947, p.11).

In the opinion of the tutor, the computer programs functioned unsatisfactorily in about a quarter of the students' (non-examination) exercises that they assessed. This was due to omissions and errors in the programming, many of which were subsequently remedied. The omissions that were not remedied mostly dealt with rhythm (it was not till the following year that a method for incorporating rhythm in the assessment programs was devised), and with value judgements (e.g. "this harmonization is very dull - you should use a wider variety of chords and more first inversions"). It was considered pointless to try to program value judgements relating to aptness or dullness because musicians are themselves not always in agreement on such matters.

Students enjoyed criticizing the examples produced by the harmonization programs, getting their own back, as it were. Their criticisms, where valid, showed them that the adherence to a few elementary harmony rules does not in itself guarantee a good harmonization. Also, by discussing the extra rules needed to improve the programs' standard of harmonization, students gained insights into those rules in particular, and Bach's style in general. For example, an awkward bass line in one computer harmonization would not have occurred if the rule forbidding leaps of augmented intervals had been employed. The class noticed this, and the harmonization programs were then enlarged to include this rule.

A comparison of the two sets of examination assessments revealed, rather surprisingly, that the computer programs and the tutor were about equally effective at detecting faults! A similar number of non-trivial faults was detected in both sets of assessments. What the tutor lost to the computer due to fatigue etc., he regained by detecting errors that were too subtle for the programs at their current stage of development. However, as
the scope of the computer programs is increased they should be able to pick up more mistakes.

CONCLUSION: Unmusical harmonizations produced by computer programs that employ a limited number of harmony "rules" can be used to demonstrate the shortcomings of those rules.

4.5.2. EXPERIMENT 2 - EVALUATION

In the six months following Experiment 1, the scope of the assessment programs was enlarged to encompass virtually all the restrictions and "undesirable" stylistic features listed in Tables 4.1 and 4.2. In addition, the harmonization programs were improved to the level reported in Chapter 5, and they were incorporated in the assessment programs in the manner described in Section 4.2. This new, radically altered assessment system was now evaluated in the course of Experiment 2.

METHOD: During February and March of 1976, students in an undergraduate harmony class were set three assignments which were to be assessed with the aid of the computer. The assignments were administered in the following way:

Week 1: Each student was given the same melody to harmonize (henceforth referred to as Assignment 1).

Weeks 2 and 3: A new melody was distributed for the class to harmonize (Assignments 2 and 3, respectively). The students' harmonizations of the previous week's assignment were collected and played on the organ keyboard (in the manner described in Section 4.4) for assessment by the programs. The resulting assessments were discussed in detail with a Senior Lecturer of the Music Department, who made suggestions as to how the assessments could be improved. They were then given to the students in time for them to consider the points raised and apply them to the current week's work. During the next few days, any small alterations needed in the computer programs were made.

Week 4: The harmonizations from week 3 were collected (together with any late work), and assessed by the programs. These assessments were critically evaluated (as in weeks 2 and 3) and distributed to the class. Then, students were invited to comment on the experiment in general and on any of the programs' comments in particular.

Participation in the experiment was on a voluntary basis; and the Head of the Music Department (i.e. the "Full Professor", in U.S. terminology) even submitted three of his own "test harmonizations" (two in week 2 and one in week 4) for assessment by the computer programs.
FIGURE 4.3

The student harmonization at (a) is so abysmal that the computer programs cannot detect all the "errors". However the programs' alternative harmonization, at (b) is a good one, and happens to use the bass line suggested independently by the music professor, at (c).
Because the computer reharmonization is based on the student's work, two contrasting student harmonizations of the same melody receive very different alternative harmonizations, shown at (a) and (b).

**FIGURE 4.4**

The assignment being marked is...

E - D - C - B - C -
A - B - A - C - G - G -
C - G - E - D - E -
A - G - A - G - C -
VI VI VI VI

* CHORD 1 TO CHORD 2*

I have discovered parallel fifths between soprano and bass.

* CHORD 2 TO CHORD 3*

There is more than an octave between the alto and the tenor.

* CHORD 3 TO CHORD 4*

I have discovered parallel octaves between alto and bass.

Strange progression

**NUMBER OF MISTAKES = 3**

Good work, but try to be more careful.

Here is a possible harmonisation:

E - D - C - B - C -
A - A - A - C - G - G -
C - D - E - G - C -
A - F - C - G - C -
V I V I V I

* CHORD 1 TO CHORD 2*

Leading note fails to resolve.

There is an illegal leap in the alto II

* CHORD 4 TO CHORD 5*

Strange cadence

**NUMBER OF MISTAKES = 2**

Good work, but try to be more careful.

Here is a possible harmonisation:

E - D - C - B - C -
G* F - E - E - E -
B - A - A - G - A -
C - F - C - E - A -
V I V I V I V I

* CHORD 1 TO CHORD 2*

I have discovered parallel fifths between soprano and bass.

* CHORD 2 TO CHORD 3*

There is more than an octave between the alto and the tenor.

* CHORD 3 TO CHORD 4*

I have discovered parallel octaves between alto and bass.

Strange progression

**NUMBER OF MISTAKES = 2**

Good work, but try to be more careful.

Here is a possible harmonisation:

E - D - C - B - C -
A - A - A - C - G - G -
C - D - E - G - C -
A - F - C - G - C -
RESULTS: When evaluating the programs' performance, the senior lecturer checked each assessment to see whether

(i) all of the student's errors were recorded,
(ii) all of the programs' comments were valid, and whether
(iii) the computer programs' alternative harmonization (where applicable) was satisfactory.

An assessment was adjudged adequate (i.e. the programs had fulfilled their functions properly) only if it satisfied all of the conditions (i), (ii) and (iii), above.

Assignment 1: From a total of twenty-three harmonizations, twenty-one were considered to have been adequately assessed by the programs, the other two having satisfactory alternative harmonizations. The worst assessment (by the programs) is shown in Figure 4.3 together with the professor's assessment of the same harmonization. The computer had just not been programmed to cope with such inept work. It is interesting to note that the bass line recommended by the full professor is identical with the one suggested by the programs in their alternative harmonization.

One imaginative student submitted a harmonization in the key of A minor. The programs analysed and assessed it correctly, providing an alternative harmonization - also in the key of A minor (see Figure 4.4). As a result of the way in which the computer had been programmed, there was a tendency for the more unorthodox work to receive the more unusual alternative harmonizations (see Figure 4.4 for another such example).

Student standards (of harmonization) varied considerably: three harmonizations did not contain any of the rule violations or stylistic features listed in Tables 4.1 and 4.2, whereas one student's work featured thirteen of them!

Assignment 2: Because of the harmonizing programs' injudicious use of a second inversion (at the fourth chord in Figure 4.1), the senior lecturer judged two alternative harmonizations to be unsatisfactory. Altogether, ten harmonizations out of fourteen were considered to have been adequately assessed (e.g. Figure 4.5).

Assignment 3: The quality of student harmonizations ranged once again from the inept to the excellent (see Figure 4.6). One student attempted to use passing notes, which was more than she - or the programs - could handle. Sixteen harmonizations out of eighteen were considered adequately assessed.

General: In every single assessment the programs' chord analysis (e.g. I, II, IV, etc.) was correct, showing up student carelessness on four occasions (see Figure 4.6).

Out of a total of 55 harmonizations from the three assignments, more than three quarters (47) were considered to have been adequately assessed by the computer programs.
The assignment being marked is...

B-- D-- F-- F-- E-- C-- B--
F-- F-- F-- F-- A-- D-- F-- D--
B-- G-- C-- C-- G-- F-- F--
D-- A-- F-- G-- A-- B--
I II III IV V VI VII

******************************************************************************
* CHORD 5 TO CHORD 6*
******************************************************************************

There is more than an octave between the alto and the tenor.
The major third is doubled.

******************************************************************************
TRY TO GET THE TENOR PART A LITTLE HIGHER IN FUTURE.
NUMBER OF MISTAKES = 1

GOOD WORK, BUT TRY TO BE MORE CAREFUL.

HERE IS A POSSIBLE HARMONISATION:

D-- D-- F-- F-- E-- C-- B--
F-- G-- F-- F-- A-- D-- F-- F--
D-- D-- C-- C-- B-- C-- D--
B-- R-- A-- F-- G-- A-- B--
I VII VII V IV V VII

FIGURE 4.5 The programs provide constructive criticism by demonstrating how the tenor part can be improved by a redisposition of the parts.
During the experiment the alterations made to the programs comprised the addition of one new stylistic feature (number (v) of Table 4.2) and the tidying up of existing feature detection routines to close unexpected loopholes (e.g. allowing for the unlikely possibility of a student's commencing a harmonization with a second inversion - as happened in the harmonization shown in Figure 4.3). Also, the format of the printout was changed in accordance with suggestions from the music professor.

Students expressed their appreciation of the objectivity and thoroughness of the computer programs, as well as of the challenge of passing judgement on their own work, using the computer assessment as "evidence".

CONCLUSION: Students' four-part harmony exercises can be assessed with the aid of a computer, in a classroom situation.

THE ASSIGNMENT BEING MARKED IS...

C" A" F" D" C" B" A"  
C F C F E D C"  
A A D A A G A  
A C B D E A  
I IV V (VII) I

WELL DONE! PISTON WOULD HAVE BEEN PROUD OF YOU!!

FIGURE 4.6 A successful harmonization! Note however that the programs' chordal analysis shows the student that her chord indication for the dominant seventh (arrowed) is not correct.
4.6. SUGGESTIONS FOR FURTHER DEVELOPMENT

Preceding sections describe the manner in which programs assess student harmonizations. Each harmonization passes through five stages of processing: (1) input, (2) chordal analysis, (3) "error" detection etc., (4) reharmonization (if applicable), and (5) output. This section suggests ways in which input and output can be speeded up and operator errors can be reduced. In addition, it is explained how results obtained elsewhere (cf. Winograd, 1968, and Lovelock, 1947) might be used to increase the sophistication of the analysis and error detection programs.

The time taken to input a harmonization via the organ keyboard usually represents over half the duration of the entire assessment procedure (as outlined in Section 4.4). Of the five stages of processing mentioned above, the input stage is the one most susceptible to operator error (interactive editing routines developed by Tucker, 1977, are available for the correction of this type of error). This stage requires the services of a keyboard player, proficient at sight-reading, to play harmonizations into the computer. Input times of more than a few seconds, operator errors and keyboard player can all be dispensed with if the student's harmonization is inputted directly from the manuscript. Optical scanning techniques would be ideal for this task, but as yet they have not been developed to allow the input of hand-written manuscript (cf. Prerau, 1971). The next best method seems to be to use a mark-sense reader. This device enables marks made in certain positions of a specially prepared computer card to be read directly into the computer.

Durrenmatt et al (1970) have used mark-sense cards to input music to computer programs. As a means of batch-processing students' music exercises this method seems ideally suited to CAI in music theory. As an indication of the way harmony could be inputted via mark-sense cards, Figure 4.7 illustrates a hypothetical example of a student harmonization notated on such a card. The card shown, contains all the pitch and timing information required by the analysis programs described in Section 4.3. It also explicitly notates doubling and displays a chord that cannot comfortably be played on the organ - both of these would normally require editing, as described in Section 4.4. In fact, by noting the names of the notes, the mark-sense card illustrated provides more musical information than is inputted to the computer programs described in Sections 4.3 and 4.4.
FIGURE 4.7 A hypothetical example of a Mark-sense card for inputting harmony directly into a computer.
A faster and more convenient method for outputting the computer assessment than the one described in Section 4.4 would be to use an on-line Xerox printer (cf. Smith, 1975). This would permit the rapid output, on a single sheet, of typed messages and conventional musical notation, the latter being of a superior quality (as demonstrated by Smith, 1975) to the music printed by most other computerized graphics techniques presently available (for a survey of such techniques see Howarth, 1977).

If an attempt is made to enlarge the scope of the assessment programs, several advanced aspects of harmony should be incorporated, such as unessential notes, modulations, discords and chromatic chords (this is the order that Lovelock, 1947, introduces them in his textbooks). It may be possible to analyse harmonizations with respect to the above aspects by using the parsing programs of Winograd (1968). Moreover, Lovelock (1947) presents extensive rules and recommendations in a precise and unequivocal manner. This may well render many of them amenable to representation in computer programs. These programs might then be used in conjunction with those of Winograd (1968) to detect rule violations and "undesirable" stylistic features relating to the more advanced aspects of harmony listed above.

For the reasons given in Section 5.5, it is likely to be extremely difficult to extend the harmonizing programs to deal in a musically acceptable manner with different types of passing notes and modulations. Thus, the complexity with which students' harmonizations can be reharmonized (so as to eliminate errors) is likely to lag behind any extensive improvement of the analysis and detection programs. This discrepancy would limit the effectiveness of the reharmonization as constructive guidance, and probably lead to its being abandoned (when assessing more advanced harmonizations), which would be a pity.

Finally, a word needs to be said about computer-aided self-instruction in harmony. The system described in Sections 4.2 to 4.5 can also be used by a student to pinpoint errors in a harmonization, which can then be corrected by the student before having any new (or remaining) errors indicated. This interactive self-teaching, in which the programs' alternative harmonization is ignored by the student when making corrections, proceeds in a "natural" manner with music being "played into" the computer. Notes and chords can be quickly altered - for the purposes of correction or experimentation - using the editing procedure described in Section 3.3.3. With extensive modification of the input/output programs the harmony assessment system could be transferred to the PLATO network of self-instruction computer terminals (see Peters, 1975), thereby bringing the benefits reported here to a larger body of students. Although the input of a harmonization using the touch-sensitive PLASMA terminal (of the PLATO system - cf. Paulson, 1976) is slower than using an organ keyboard, it can be more convenient for a student who is harmonizing at the terminal. The PLATO sound output facility could also allow the student to hear his (or her) harmonization, as well as the "corrected" version.
4.7. CONCLUSIONS

This chapter reports the design and trial of computer programs to provide CAI in basic, four part harmony. Preliminary results indicate that the system which has been developed provides a useful extension to existing CAI in music theory. One reason for providing a new level of sophistication is that existing systems, for the most part restricted to typewriter input, have been limited to the teaching of simple tasks e.g. the naming of triads (a detailed review of existing systems is presented in Section 2.4.6). Now, however, the facility by which music is input to a computer via an organ keyboard (as developed by Tucker et al, 1977) has enabled programs to deal with music directly. The advantage of this convenient form of input has been exploited with specially designed programs which analyse a student’s harmonization and then assess it for standard "mistakes" and points of style of a technical nature. When errors are detected, constructive guidance is provided - by the programs - in the form of an alternative harmonization based on the students’ work. Section 4.2 explains how, in accordance with the main contention of this thesis (as set out in Section 1.2) the computer programs deal with the mechanical aspects of harmony instruction, freeing the main attention of the instructor for more creative aspects.

The experiment reported in Section 4.5.1 describes how unmusical harmonizations produced by a computer program employing a limited number of harmony rules, can be used to demonstrate the shortcomings of those rules. Another experiment, reported in Section 4.5.2, shows that students’ four part harmony exercises can be assessed with the aid of a computer in a classroom situation.

As explained in Sections 4.2 and 4.4, desirable features of the computerized harmony-assessment system include its meticulousness and its ease of operation - little prior knowledge about computers is required to use it. Finally, the success of the system is indicated (in the experiment reported in Section 4.5.2) by the low proportion (less than a quarter) of student assessments requiring changes or extra comments by the tutor.
5. INTERACTIVE HARMONIZATION IN A PARTICULAR STYLE

5.1. THE COMPUTER AS AN AID TO COMPOSERS

Since the advent of the digital computer there have been many attempts to use it for musical composition. With analogue and hybrid computers also becoming available to composers, it has been possible to use computers for performance as well as for composition. Special studios have been constructed (cf. Sandlund, 1972; Grogono, 1973; and Di Giugno, 1976) and an impressive list of compositions and computer languages (cf. Mathews, 1969; Vercoe, 1973; and Truax, 1977) has emerged.

The inspiration provided by probability theory, to Hiller and Baker (1964) for their "Computer Cantata" and to Xenakis (1971) for his "Morisma-Amorisma", could not have been taken advantage of without computers. However, these composers interacted very little with their computers once they had written their programs. The author feels strongly that the place of the computer in musical composition is not in being creative (that is the province of human beings) but in helping musicians to sift and assess far more musical combinations than would otherwise be possible. This means that programs must be designed to enable composers to interact with computers in real time, thereby providing immediate feedback for successive refinement of compositions and enabling a work to be completed while the composer's inspiration remains in his consciousness.

The MUSIC V system of Matthews (1969) in conjunction with GROOVE (see Matthews and Moore, 1970), provides such interaction, allowing users to hear the effects immediately. However, the user must specify the parameters (e.g. pitch, duration, waveform, and envelope) of every note. By working at such a basic level, the composer shares the donkey work with the computer programs. It is much more desirable that computer programs do virtually all the donkey work, leaving composers free to interact at higher levels (controlling stylistic features, for example) but still able to manipulate individual notes on occasion.

Barbaud and Blanchard (1966) go some of the way towards computerizing the donkey work when they program many techniques of combinatorial mathematics, including the standard permutations of the twelve-tone row. They allow composers to control not only the notes, but also the manner in which they are combined. Simple commands can generate new sequences of notes from existing ones, depending on the combinatorial process invoked.

As well as providing interactive manipulation of groups of notes, Smith (1972) with his SCORE program uses a property of computers, that humans do not possess - randomness. As pointed out by Buxton (1977) "one of the drawbacks with SCORE, however, is that while the specification of the data to the programs is interactive, its acoustic realisation is not necessarily so. More recently, Frykberg (1978) has composed pieces using a system (cf. Vaughan,
1977; see also Tucker, 1977) in which both the composition procedures and their acoustic realisation are interactive.

The POD system for interactive composition (cf. Truax, 1977) extends the degree of high-level control exercised by the musician. The composer specifies musical parameters at different levels in an attempt to combine statistical distributions of sound into well-formed musical structures.

The distinction must be made between music played by a computer (as with advanced types of synthesizers (cf. Moog, 1967; and Olsen, 1971) and music composed with the aid of a computer, by which is meant the specification of musical parameters (e.g. pitch, duration and loudness) by a musician using a computer program. In this thesis the term "program-aided composition" is used to denote a piece of music generated in the latter fashion.

The style of a program-aided composition is determined by the constraints governing the generation of note combinations. The set of constraints may be simple (as in the case of serial composition for a solo instrument) or extremely complex, as when composing a classical symphony or baroque fugue. By experimenting with constraints, new styles of program-aided composition can be discovered and existing styles modified. These stylistic constraints form part of "musical syntax", which can be considered to be a branch of linguistics. Laske (1974) and Smoliar (1976) are currently attempting to translate musical linguistics into a programming language, but no musical composition has yet been produced using this approach.

Musical style synthesis, and high level interaction during program-aided composition are fields that warrant further investigation. To demonstrate how a computer can be programmed for style synthesis, and to investigate various levels of interaction, a traditional style has been taken as a model and an interactive system developed for harmonization in a style as close as possible to this model.

To date, the only significant attempt to imitate an existing style by means of computer programs seems to be that of Rader (1977). He uses harmony rules and a stochastic process (i.e. each note is chosen from the preceding note according to a set of probabilities) to imitate Bach's first Two-part Invention. Even though the detailed structure of the program-aided composition is specified by Rader to be the same as that used by Bach (in the Two-part Invention) the results do not bear comparison with Bach, in this author's opinion. Rader does not interact with his programs in real time. Indeed, the music produced for a fixed set of constraints can vary a great deal on successive generations (due to the probabilistic nature of the generative process).

This chapter presents the results of a study of the use of computer programs to produce four-part harmonizations (SATB, i.e. soprano, alto, tenor, bass) in the style that J.S. Bach used in his 371 chorale harmonizations (see Riemenschneider, 1941). The Bach chorales have been chosen as a model because they form a
stylistically consistent and musicologically complete group of works. In addition, this style has been formalized by the definition of numerous harmony "rules", such as those due to Lovelock (1947) and Piston (1949). These rules can be used as the "stylistic constraints" described earlier.

The study focusses on two main areas. The first is the development of a system to harmonize adequately without interactive guidance, and the second involves several types of interaction in which the programs do various amounts of donkey work.

Figure 5.1 is a typical example of the results obtained in the first area. It shows a harmonization which is "full of life" (i.e. it keeps moving harmonically), but which contains an

![Figure 5.1](image1)

**FIGURE 5.1** An example of a harmonization completed by the program without interaction from the musician. (The music shown in this figure - and in Figures 5.4, 5.6b and 5.7 - has been printed using the computerized music-typesetting aid - see Howarth, 1977).
occasional inapt chord. For example, the fifth note would be better harmonized with the chord of II B, as is done by Stewart and Pritchard (1929). The harmonization shown in Figure 5.1 also features several "unusual" chord progressions - e.g. the interesting "twist" at the ending. Unexpected progressions of this nature can suggest original ideas to the musician. Also, the harmonization (shown in Figure 5.1) is technically correct in that it obeys the harmony rules listed in Section 5.2. The interactive procedures described in Sections 5.3 and 5.4 are necessary to allow the musician to correct any inapt chords. They may also be used to alter the "unusual" progressions where desired.

The next section outlines the harmonization problem, indicating its magnitude. Then, Section 5.3 describes in detail how a melody is harmonized by the programs, and explains the various ways that the musician can interact with them. A selection of musical examples obtained using the interactive procedures is presented in Section 5.4. The good and bad points of these harmonizations are assessed. In Section 5.5, ways are proposed for extending the programs to make them harmonize modulations, and melodies containing passing notes. Section 5.5.3 reports an attempt to improve the quality of the programs' harmonizations by imitating Bach's use of root pitches. Finally, Section 5.6 summarizes the main findings of this chapter.
5.2. THE HARMONIZATION PROBLEM

The principal features of a four-part harmonization in the style of Bach are the melody, bass and root pitches. When writing four-part harmony, a composer’s choice of these features is subject to certain restrictions, which are summarized in Table 5.1 with the more important ones, in the author’s opinion, shown first. Since it is felt that the appreciation of chorale melodies is influenced to such a degree by subjective judgments on the part of musicians (see Table 5.1), it is considered that few people are likely to find computer generated chorale melodies satisfactory. On the other hand, since the bass notes and root pitches are affected much less by subjective judgments, in the author’s opinion, they are much more suitable for computer generation. Therefore, programs have been designed which harmonize in such a way as to leave the melody completely in the hands of a musician, who interactively guides the programs in their choice of bass notes and root pitches.

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>RESTRICTIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melody:</td>
<td>1* The mood of the harmonization</td>
</tr>
<tr>
<td></td>
<td>2 Voice ranges &amp; awkward vocal leaps</td>
</tr>
<tr>
<td></td>
<td>(i.e. it must be singable)</td>
</tr>
<tr>
<td></td>
<td>3* Interest</td>
</tr>
<tr>
<td>Bass:</td>
<td>1 Singability</td>
</tr>
<tr>
<td></td>
<td>2 Movement of the soprano &amp; other parts</td>
</tr>
<tr>
<td></td>
<td>3* Interest</td>
</tr>
<tr>
<td>Root pitch:</td>
<td>1 Tonality</td>
</tr>
<tr>
<td></td>
<td>2 Avoidance of &quot;weak&quot; progressions</td>
</tr>
<tr>
<td></td>
<td>3 Preference for &quot;good&quot; progressions</td>
</tr>
<tr>
<td></td>
<td>4* Harmonic rhythm, which depends on mood and interest</td>
</tr>
</tbody>
</table>

TABLE 5.1 Restrictions affecting students in their choice of the principal features of four part harmonizations. Asterisks identify those restrictions most affected, in the author’s opinion, by the subjective judgements of musicians.
BASIC HARMONY RULES

No consecutive fifths or octaves.
No exposed fifths or octaves.
No doubled leading note.
The leading note must rise, except in a cadence or descending scale passage.
The harmonization must finish with a cadence.
The chord progression II - I is forbidden.
Parts must not cross, or overlap by more than a semitone.
There may not be more than an octave between S & A, or between A & T.
No doubled major thirds.
The leap of a diminished fifth must be followed by a note within its range.
An octave leap must be followed and preceded by notes within its compass.
Second inversions may be either cadential, or approached and quitted by step in the bass.
SATB must remain within prescribed tessitura.
A part may not leap an augmented interval, a major seventh, or any interval greater than an octave.
If the melody note is repeated weak to strong, the chord must be changed.
All first and second inversions of major and minor chords must be complete.

TABLE 5.2 Basic rules used in the program-aided harmonizations. They are taken from Lovelock (1947) and Piston (1949).
5.2.1. NUMBER OF DIFFERENT POSSIBILITIES WHEN HARMONIZING

The magnitude of the "harmonization problem" can be seen from a consideration of the freedom of choice available. Unessential notes are neglected to begin with, in order to simplify the discussion. With an eight note phrase, each note can be harmonized in approximately twenty possible ways, just using major and minor common chords. This means that there are over twenty-five billion different singable harmonizations just for these eight melody notes (cf. Barnard and Child, 1946)! By applying the harmony "rules" listed in Table 5.2, the number of simple chords "permissible", or valid, for any one melody note is reduced to about eight, which brings the number of possible harmonizations down to approximately ten million. Many of these - certainly those versions which possess identical bass lines and root pitches - will sound very similar, so much so that to the untrained ear they will probably be undistinguishable. Therefore, since there are about two possible valid root pitches and about two possible valid inversions on the average per melody note, the number of appreciably different valid harmonizations becomes approximately 65,000. However, for a musically acceptable arrangement there are only about two combinations of root pitch and inversion suitable for each melody note, - leaving a total of approximately 250 appreciably different, acceptable harmonizations of our eight note phrase.

Therefore, for a program to produce an acceptable harmonization of an eight note melody, it must be able to find any one of 250 acceptable versions from among 65,000 appreciably different valid harmonizations (obtained by applying the "rules" of harmony to all the singable possibilities). This means that, using harmony rules alone, the program has less than half a per cent chance of producing anything that the average musical person would consider acceptable. To improve the odds, it is necessary to incorporate additional restrictions - musical "hints" - into the programs. These extra rules (which are here called "derived rules" because they have been developed using the author's own harmonizing experience and from suggestions contained in the harmony textbooks of Lovelock, 1947, and Piston, 1949) are used to eliminate those harmonizations which exhibit certain stylistic features (e.g. exact repetition of a chord) which in some situations would be considered musically undesirable. The effectiveness of these derived rules is documented in Section 5.3.2. The danger here is that the good is liable to be discarded with the bad if the derived rules are too restrictive. Alternatively they may not prune away enough of the unwanted 99.5% to make any significant difference.

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The rules that are stated unequivocally in the textbooks of Lovelock (1947) and Piston (1949) are here referred to as "basic rules" (see Table 5.2) as opposed to those that have been developed by the author (the "derived rules" mentioned above). Henceforth both basic and derived rules are referred to collectively as "harmony rules". Later, the term "heuristic" (cf. Feigenbaum and Feldman, 1963) is used to mean a programming technique that uses cues in the music to decide between various possible interpretations of a musical passage (e.g. finding the most likely key at a given point). The derived rules and heuristics are discussed later in Section 5.4. The next section (Section 5.3) describes how the harmonizing process is implemented on an interactive system developed by Tucker et al (1977). The musician's actions are outlined to convey the ease of operation and flexibility of interaction.

<table>
<thead>
<tr>
<th>CUE</th>
<th>IMPLIED TONALITY</th>
<th>&quot;WEIGHT&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semitone leap</td>
<td>the second note</td>
<td>major &amp; minor</td>
</tr>
<tr>
<td>Perfect 4th upwards or perfect 5th downwards leap</td>
<td>the second note</td>
<td>major &amp; minor</td>
</tr>
<tr>
<td>Semitone leap downwards</td>
<td>major third below the second note</td>
<td>major</td>
</tr>
<tr>
<td>Semitone leap downwards</td>
<td>perfect 4th above the second note</td>
<td>minor</td>
</tr>
<tr>
<td>First note of the melody</td>
<td>the first note</td>
<td>major &amp; minor</td>
</tr>
</tbody>
</table>

Table 5.3 Soprano voice leading cues used for finding the key e.g. F followed by E suggests that either C major or A minor is the key.
5.3. OPERATION OF THE INTERACTIVE SYSTEM

To start the procedure, the command "RECORD" is typed on the console typewriter (the layout and operation of the computerized aid for musicians are described in Section 3.3). Next, the musician plays a melody on the organ keyboard. The subsequent typing of "SCORE" causes the musical notation for what has just been played to appear on the screen of the storage oscilloscope. Any mistakes are corrected by electronically "pointing" to them and then replacing them with the desired notes (this editing process which is outlined in Section 3.3.3 is described in detail by Tucker, 1977). Then, "HARMONIZE" is typed. This activates programs which analyze the melody with respect to key, passing notes and modulations (the latter two of these are neglected for the moment, but are discussed in some detail in Section 5.5). The key is found by using "semantic heuristics" and a process of elimination as follows: Initially, all keys are considered possible, but as each note is processed those tonalities to which it cannot belong are eliminated. The voice leading cues (see Table 5.3 - note the "weight" assigned to each cue) that occur in the melody have their corresponding weights totalled for each key still remaining as a possibility by the end of the piece. The tonality with the highest total weight is then adopted as the key of the entire melody. However, if so desired, the program may be over-ruled.

5.3.1. CHOICE OF CHORDS

Next, the melody is harmonized in four parts in the following manner. The best root pitch for the first melody note is found by using Piston's (1949) table of preferences. All singable arrangements of A, T and B (i.e. alto, tenor and bass) for this root pitch are calculated and stored. The same is done for the second melody note (note 2). Next, all the A-T-B combinations for note 2 are tested against the first A-T-B combination for note 1 using the harmony rules listed in Table 5.2 and Table 5.4. Those combinations that are valid (i.e. they do not disobey any rules) are arranged in order of "suitability" depending on the amount of part movement, the existence of contrary motion between S and B, and the completeness of the chords. Then, the first A-T-B for note 1 and the "most suitable" of the valid A-T-Bs for note 2 are chosen as chords 1 and 2 respectively. Next, the program moves on to choose chord 3 in a similar manner, by finding the best root pitch and most suitable A-T-B to follow chord 2. The program continues in this way until it finishes the piece with an appropriate cadence.

At all times, the program has available to it every valid A-T-B (arranged in order of suitability) for each melody note that it has passed. This is necessary, because often there is no permissible A-T-B available to follow a particular chord. This may be due to awkward leaps in the melody, to interactive rejection of certain chords, or just to the way the preceding chords have evolved. When such a situation arises, the program takes the next best A-T-B combination for that chord and tries to
FIGURE 5.2 Flow diagram summarizing how the program chooses each chord. "Choose RP(I)" means "choose the best available root pitch for the Ith melody note". "Generate ATB(I)" means "find all singable A-T-B combinations for melody note I, based on RP(I)".

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proceed again. If the supply of A-T-Bs with the present root pitch is exhausted (for that particular note), the next best root pitch is employed and a new supply of A-T-Bs is generated. Only when all possible root pitches and A-T-Bs have been rejected for that note, does the program go back to the note before and choose its next best A-T-B. This procedure is summarized in Figure 5.2. In this way, harmonization is carried out in a predominantly forward direction, back-tracking only where necessary.

By following the above procedure, the program eventually either produces a valid harmonization or arrives back at the first note having tried and rejected all the possible harmonizations. When the former happens, the note names and chord analysis of the harmonization are listed on the display screen. The program then causes the music to be played on the organ, and the musician may hear it over again any number of times by depressing an appropriate key on the typewriter. At this stage the musician interacts with the program at three different levels: global, dealing with the overall style; regional, affecting chords and their immediate surroundings; and local, in which individual notes and chords are manipulated by themselves.

### IMPROVING THE PROGRAMS' HARMONIZATIONS

<table>
<thead>
<tr>
<th>DERIVED RULE</th>
<th>MUSICAL EFFECT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use Piston's (1949) preferences when choosing root pitches.</td>
<td>More musical progressions</td>
</tr>
<tr>
<td>Avoid repetition of the same root pitch &amp; inversion, with less than 2 intervening chords.*</td>
<td>Prevents &quot;stagnation&quot;, and deals with the last rule in Table 5.2</td>
</tr>
<tr>
<td>Scan 3 notes ahead, and choose root pitches accordingly.</td>
<td>Eliminates abrupt endings</td>
</tr>
<tr>
<td>Minimise part movement</td>
<td>Smoother progressions and occasional countermelodies</td>
</tr>
<tr>
<td>Encourage contrary motion between soprano &amp; bass.</td>
<td>Stronger progressions</td>
</tr>
<tr>
<td>Prefer complete chords.</td>
<td>Fuller harmonies</td>
</tr>
</tbody>
</table>

**TABLE 5.4** Derived rules for improving the quality of computer harmonizations. An asterisk denotes a rule used only when harmonizing in a forward direction (see Figure 5.2).
5.3.2. METHODS OF INTERACTING WITH THE PROGRAMS

The types of interaction available are summarized in Figure 5.3 and Table 5.5, and the musician puts them into effect by using the four following methods (arranged in order of increasing musical sophistication):

1. rejecting a particular chord,
2. specifying a root pitch for a particular note,
3. altering the derived rules, and
4. replacing a note or an entire chord with another.

Methods (1) and (2) are straightforward for a musician to employ, but when the programs respond, harmony rule considerations may require the changing of adjacent chords. Method (4) does not directly involve the harmonizing program and so it can be used whenever the musician wishes to "break" any conventional harmony rule. The musician may subsequently use the harmony-assessment programs described in Chapter 4 to detect any rule violations brought about by this interaction.

Before Method (3) can be understood, the derived rules must be discussed. It is necessary to invoke these derived rules because the basic rules merely outline what is stylistically inappropriate. When it neglects the derived rules, the program produces harmonizations only marginally better than the "inappropriate" versions rejected by the basic rules. This is illustrated by Figure 5.4, which shows the dramatic improvement effected by using a derived rule (based on Piston, 1949) which prefers certain root pitch progressions.

The implementation of the last three derived rules of Table 5.4 contains the "musical intelligence" of the harmonizing programs described here. Every permissible chord considered during the harmonization process is assigned a value \((k+m+n)\), where \(k\) is the total number of semitones leapt by the A, T and B from the preceding chord. Usually \(m=n=0\) except in two particular circumstances. The program sets \(m=3\) when S and B move in similar motion. It sets \(n=5\) if the chord is incomplete. The most suitable chord is then taken as the one with the lowest value of \((k+m+n)\). In this way smooth inner parts are preferred, as are contrary motion between soprano and bass, and complete chords (all of which are musically desirable). The program stores the value of \((k+m+n)\) for every chord examined during the harmonizing process. These values are used when back-tracking, to find the next best chord at any point.

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FIGURE 5.3 Flow diagram summarizing the interaction process. Interaction outside the harmonization program is indicated by *.
FIGURE 5.4 Example illustrating the benefit of using derived rules: (a) melody harmonized using only basic rules, (b) the same melody harmonized using the same basic rules together with derived rules for the root pitches based on Piston’s (1949) preferences.

When interactively altering the derived rules (using Method 3), the musician may change the manner in which the suitability of a chord is evaluated. By assigning the values to which $m$ and $n$ are set, overall emphasis on contrary motion and chordal completeness can be controlled. The musician may also invoke additional derived rules which discourage (a) second inversions, (b) repetition of root pitch in adjacent chords, or (c) repetition of root pitch with only one chord intervening. The first of these, results in a rather naive sounding harmonization, while (b) and (c) introduce a feeling of onward movement or restlessness, or jerkiness, depending upon the melody being harmonized.
### TABLE 5.5 Interactive commands available to the musician

<table>
<thead>
<tr>
<th>INTERACTION</th>
<th>COMMAND</th>
<th>PROGRAM'S INTERPRETATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Local</td>
<td>Insert, change or delete notes or chords</td>
<td>New notes are assigned note names according to the tonal context.</td>
</tr>
<tr>
<td>Regional</td>
<td>Reject a chord</td>
<td>Either the root pitch or inversion is altered. If a lot of backtracking results, the interactive advice is stored &amp; ignored (because the context has changed).</td>
</tr>
<tr>
<td></td>
<td>Specify a root pitch</td>
<td>This command specifies a class of chords, one of which is chosen by the program. Preceding and following chords are altered, if need be, to accommodate this change.</td>
</tr>
<tr>
<td>Global</td>
<td>Change the way in which an ATB’s suitability is determined.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Suppress second inversions.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Prevent repetition of root pitch.</td>
<td></td>
</tr>
</tbody>
</table>

After the musician has finished - for the time being - employing any or all of the first three methods of interaction, the program reharmonizes the melody, changing only those chords affected by the interaction. Then this new harmonization is automatically played back as before, and a new round of interaction begins (see Figure 5.3). All interactive changes, excepting those involving the additional derived rules (a), (b) and (c) described above, are carried forward with successive interactions, unless overruled by the musician. When the interaction with the
harmonization programs is completed, the programs add unaccented passing notes to the A, T and B parts, if desired. To do this, the programs insert a passing note into each of the major or minor third leaps in these parts, providing it obeys the additional harmony rules listed in Table 5.6.

**ADDITIONAL RULES WHEN USING PASSING NOTES**

A passing note must not move in parallel octaves or parallel fifths with any part.

A passing note may not strike a dissonant interval with another part.

In a perfect cadence, the only permitted passing note is the subdominant note.

**TABLE 5.6 Rules used by the programs when they add unaccented passing notes to a harmonization.**

Next, the musician may use the editing facilities (described in Section 3.3) to "touch up" the composition. Notes or chords may be changed, and passing notes added or deleted. Subsequent typing of the commands "PLAY" and "SCORE" causes the edited harmonization to be respectively played back and notated on the screen. The touching up process is interactive in the sense that the musician receives immediate feedback, both visual and aural, following any changes that are made. Various amendments can be tried out before deciding on the final version, thereby concluding the interactive procedure.
FIGURE 5.5 Successive stages of interactive harmonization by a harmony ingénue. At (i) is the program's harmonization. At (ii) are shown only the chords altered by the programs to accommodate the rejection of the two arrowed chords (little notes represent unchanged notes). (iii) shows the program's adjustment to the 0 rejection of another arrowed chord. Notice that the earlier rejections are still accommodated, at "a". (iv) is the final version in which passing notes have been added by the programs.
5.4. EXAMPLES OF HARMONY PRODUCED INTERACTIVELY

As explained in Section 5.3.2 there are four different ways of interacting with the programs, each method demanding a different degree of musical sophistication. The author persuaded a friend of his, who is also a musician, to attempt to interactively harmonize a chorale melody. Figure 5.5 shows the steps involved in producing a harmonization by the least sophisticated method of interaction - that of rejecting unwanted chords (i.e. method 1 in Section 5.3.2). In the discussion of the following examples, the people who interacted with the programs are identified by the initials of their last names.

C, a singer with little formal training in music theory, sums up his knowledge of harmony as "I don't know much about harmony, but I know what I like." Figure 5.5 illustrates the way the programs responded to C's interaction with them. First the melody was "played in" and its key correctly identified by the programs as being F major (the procedure involved is described in Section 5.3). The programs then added the A, T and B (alto, tenor and bass) parts as shown at (i) in Figure 5.5. The two chords that C disliked were rejected by him (they are indicated by arrows in the figure). They were then replaced by the programs with the two chords marked (a). The resulting harmonization is illustrated at (ii) (in Figure 5.5). Only the altered chords are shown, so as to indicate the effect of the interaction. In this harmonization ten other chords are seen to be altered by the programs, in addition to the two rejected by C. As explained in Section 5.3.2, the interactive changing of a chord may cause harmony rules to be violated, in which case the surrounding chords are altered by the programs to accommodate the change. In the harmonization shown at (iii) in Figure 5.5, a further round of interaction has taken place as a result of another rejection by C (of the arrowed chord in the harmonization shown at ii). C was satisfied with this new harmonization, which does not contain any of the chords he had rejected previously. To accommodate this last rejection, which results in the new chord shown at (b), five other chords are seen to be altered. Of these five, the one marked (a) was adopted in accordance with the initial round of interaction. Finally, the programs added passing notes to produce the harmonization shown at (iv) in Figure 5.5, with which C was well pleased.

The above example highlights a weakness of the harmonizing programs - namely the occasional use of an inappropriate second inversion. The chords rejected by C were all second inversions (even though he was not aware of this fact when rejecting them). Such inappropriateness could be avoided by the use of extra harmony rules (e.g. restricting second inversions to be either cadential or passing). It might also be avoided by altering the semantic heuristic described in Section 5.3.1, to make the programs prefer root position or first inversion chords if there is a choice - all other things being equal.
FIGURE 5.6 (a) - The result of interactively harmonizing the same melody shown in Figure 5.5, by using a variety of methods (1, 2 and 4 of Section 5.3.2). (b) - Bach's harmonization of the same melody. "*" denotes a chord whose root pitch has been specified by the musician.
In the next example, L who has passed his first year undergraduate harmony course, interacts with the programs at more sophisticated levels than did C, above. Figure 5.6 illustrates, at (a), the end result of L's harmonizing a melody using the interactive methods numbered (1), (2) and (4) in Section 5.3.2. The melody is the same as the one interactively harmonized by C (see Figure 5.5). L's harmonization was obtained as a result of 3 reharmonizations by the programs (which then added passing notes), after which notes were interactively edited. Altogether, five root pitches were specified (at the positions marked with an asterisk, in Figure 5.6), two chords were rejected, three passing notes deleted and four notes changed. L was satisfied with the resulting harmonization, but he would have preferred that the programs had not made the alto and tenor parts double the F at the start of the penultimate bar.

The author feels that a comparison with Bach's own harmonization, shown at (b) in Figure 5.6, is the "acid test" for the programs. The program-aided harmonization illustrated at (a) of this figure seems to need a chromatic chord (such as the fourth chord used by Bach) to dispel the monotony of the unbroken succession of primary chords in the first half. The inability of the programs to harmonize optional modulations is shown up by Bach's masterful treatment of the modulation to the dominant which is implied in the melody. Methods of extending the programs to deal with modulations and to produce more varied chord progressions are proposed in the next section. However, as is explained there, mood-affecting features such as modulations pose considerable programming difficulties with regard to "semantics" and musical context.
5.5. EXTENDING THE HARMONIZING PROGRAMS.

There are two main reasons for increasing the sophistication and quality of the harmonizations produced by the programs. Firstly, such an improvement would enable the computerized system for harmony assessment (described in Chapter 4) to deal with more advanced harmony. As explained in Section 4.6, the standard of the reharmonizing programs is likely to be the limiting factor for any increase of the musical sophistication of the assessment system. Secondly, improvements of this nature would also benefit the interactive harmonizing procedure, by reducing the amount of interaction required to produce an acceptable harmonization.

As can be seen from Figures 5.5 and 5.6, the style of the program-aided harmonizations before interactive editing differs appreciably from that of Bach. No use is made of accented passing notes, modulations, or discords. The choice of root pitches and use of second inversions are inappropriate on occasions (ways for improving the programs' use of second inversions are suggested in the preceding section). Methods are now proposed for making the computer's end products more Bach-like i.e. to incorporate modulations and more passing notes into the program-aided harmonizations. Section 5.6.3 reports an attempt to improve the programs' choice of root pitches by imitating Bach's harmonizing traits. Despite encouraging results from a context-based analysis of six Bach Chorales (described in Appendix 3), an inspection of 28 of the remaining 365 chorales shows that the traits observed in the analysis are not sufficiently general to justify inclusion in the harmonizing programs. The results presented in the following sections indicate that the programs can be adapted to produce more complex harmonizations with, however, the quality of the root pitch progressions remaining unimproved.

5.5.1. PASSING NOTES

As explained in Section 5.3.2, it is straightforward for the programs to add unaccented passing notes to the A, T and B parts of a harmonization. It is more difficult to determine which of these passing notes should actually be employed - a matter for style and personal taste to decide. At present, those passing notes that the musician dislikes may be interactively removed by editing (i.e. method 4 in Section 5.3.2). Avoidance (by the programs) of some of the more unsuitable passing notes could be achieved by invoking derived rules relating either to the contrapuntal texture or to the overall structure. In the former case, an appropriate rule might be: employ no more than two passing notes at any moment, and prefer the upper parts if there is a choice; while in the latter case a possible derived rule to invoke would be: allow the rate of occurrence of passing notes to increase just before a cadence.

A more complex task is the harmonization of a melody which contains passing notes (these are identified by the program as being the "short" notes in a melody which has been played in). The program must decide which of them are to be treated as
accented passing notes and which as unaccented passing notes (i.e. which short notes are to be harmonized as "essential" notes).

This semantic problem is probably best resolved by having the programs choose the essential notes to be compatible with Piston's (1949) root pitch preferences. However, it must be allowable to change this interpretation during the harmonizing process, especially during back-tracking, to enable all the alternatives to be evaluated. To implement this requires computer storage to hold all the alternatives while choosing the best one, or else a sophisticated programming structure to enable the program to back-track through different interpretations without "forgetting" earlier attempts with the same passage. Interactive guidance is needed to allow the musician's intentions to be carried out.

![Figure 5.7](image.png)

**FIGURE 5.7** The computer programs' harmonization of a modulation.

### 5.5.2. MODULATIONS

In the melodic analysis program mentioned in Section 5.3, modulation in a melody is detected by finding a note that is incompatible with all the keys possible at the preceding note. The new key is found by successively deleting notes from consideration, the most outdated ones being deleted first, until the remaining notes can all belong to at least one key. By employing the semantic heuristic using the voice leading cues (see Table 5.3), the most likely new key is found from the subsequent notes. Because the accumulated "weights" relating to the likely keys are at a maximum just before each modulation and the number of possible keys is at a minimum, the program is "most certain" about the key at this point. Accordingly, the program is made to scan backward through the composition, assigning the "most likely key" just before each modulation (or at the end of the piece) to all the notes occurring earlier in the melody back to and including the preceding modulation. During harmonization, the program treats the key as assigned by this process as the tonic, producing harmonizations of which Figure 5.7 is a typical, unadorned example. Extra sophistication (e.g. special harmony rules) is needed to produce satisfactorily smooth transitions between keys, and to deal adequately with abrupt modulations.
Implied or "optional" modulations in a melody are much more difficult to harmonize using computer programs. The semantic difficulties involved in deciding whether to modulate or not are considerable. Factors affecting this choice include (a) the mood of the harmonization (as with a change from major to minor mode), (b) interest (e.g. modulations that introduce tonal variety) and (c) overall tonal structure (e.g. the composition should end in the tonic key). Once the decision to modulate has been made, the type of modulation - abrupt or gradual - must be determined. This could be done by using Piston's preferences to find good root pitch progressions in both keys in the region of modulation. This process either results in an appropriate pivot chord being found, or failing that, in the use of an abrupt modulation. Because of the many possible interpretations available for each modulation, the associated computing problems become even more formidable than is the case with harmonizing passing notes (see Section 5.5.1). Additional derived rules are unlikely to solve more than a small part of the modulation problem, and for these reasons the author feels that the musician should have complete interactive control over optional modulations.

5.5.3. IMITATING BACH'S USE OF ROOT PITCHES

As pointed out in Section 5.1, the harmonizing programs occasionally choose a root pitch which is unsuitable, but which nevertheless obeys the harmony rules. Piston (1949) states that "no change in the make-up of the chords can remedy an inappropriate root [pitch] progression". Thus it is probable that by improving the choice of root pitches, i.e. by making them more Bach-like, the quality of an entire harmonization can be improved.

One way of making the choice of root pitches more Bach-like, would be to find traits in Bach's use of root pitches (in his chorale harmonizations) and then have the programs imitate these traits. The existence of such traits is hinted at by Lovelock's (1970) observations that

1. "It is in the treatment of cadences that a clearly defined "Bach idiom" is most easily displayed ... there are numerous idioms which recur time after time";

2. "Melodic approaches to the perfect cadence tend to be stereotyped, the most common being mediant - supertonic-tonic, often preceded by the subdominant."
Lovelock's comments may be augmented by the following observations obtained by direct inspection of the chorales:

3. the first note of a chorale is normally harmonized with some form of the tonic or dominant chord;

4. the resolution, in the melody, of the leading note onto the tonic is often harmonized with the dominant chord followed by either the tonic or the submediant chord;

5. a chorale melody usually implies specific phrasing, and each phrase normally ends with a cadence;

6. often a root pitch can be predicted from the preceding root pitches e.g. the root progression VI - II - V is often followed by I or VI.

Observations (1), (2), (4) and (5) above, suggest that if root pitch traits exist in Bach's harmony, then these will be linked to the melody in some way. Observation (6) suggests that such traits may also take the form of stereotyped root pitch progressions (e.g. VI - II - V - I). Appendix III presents the results of a context-based analysis of 6 chorales designed to find and identify such traits. Preliminary results suggested that Bach often uses the same root pitches to harmonize certain stereotyped melody fragments. Figure A3.1 shows four such melody fragments (indicated by brackets) in Chorales 1 and 6, all of which are harmonized with the same root pitches (when transposed into the same key) for the last three notes. Further investigations into 26 more chorales, however, indicated that only the particular melody fragment described above is harmonized with consistently the same penultimate root pitch by Bach. Thus the results of the experiment, although revealing interesting aspects of Bach's chorale style, are unlikely to be useful for improving the harmonizing programs' choice of root pitch.
The results presented in this chapter show how computer programs have been developed to produce four part harmony in a particular style. Derived rules representing formalized "musical intuition" are used to improve the musical quality of the programs' harmonizations. The musician can interact at a higher musical level than is the case with previous systems for program-aided traditional composition. The interactions reported in Section 5.4 demonstrate ways in which computer programs can do a composer's donkey work, leaving the composer to deal with more general stylistic features (such as root pitch progressions).

With the four methods of interaction described in Section 5.3.2 it is possible to achieve any harmonization of a given melody, in theory (e.g. by interactively editing). However, in practice the programs are best suited for harmonizing a melody which does not contain unessential notes, and does not modulate. As is shown in Section 5.4, the programs do not bear comparison with Bach. But if the interactive harmonizing turns out to the satisfaction of the musician, the resulting harmonization will be no worse than his or her musical judgment.
6. COMPUTER-AIDED INSTRUCTION IN PIANO PERFORMANCE

6.1. INTRODUCTION

Piano playing is a complex activity, involving many skills. In the two and a half centuries since the invention of the pianoforte, numerous treatises (e.g., Bach, 1753; Clementi, 1801), studies and exercises (e.g., Czerny, 1839; Chopin, 1829) have been published to help students acquire these skills. For the same purpose, curious mechanical devices such as the Chiroplast and Dactylium (described in Section 2.2) were invented, most of them enjoying a brief vogue before being consigned to a well-deserved oblivion. The mechanical aids that survived are the Metronome and the (nearly extinct) "Virgil Practice Clavier" (both these devices are described in Section 2.2). The metronome functions as a tempo indicator, and thereby helps musicians detect rhythm fluctuations in their playing. The practice clavier highlights errors in the synchronization of starts and ends of notes, and may also be used to strengthen the fingers. More recent inventions, namely, the tape recorder, videotape recorder and closed-circuit television (CCTV) provide pianists with the opportunity to observe reproductions of their own performance. This chapter presents a new, computerized aid - basically a subset of the interactive aid (for musicians) developed by Tucker et al (1977) - which provides pianists with different information about their playing from that offered by existing aids. In particular, it provides detailed feedback about note durations and aspects of rhythm. By slowing down the playback of a pianist's performance, the computerized aid enables errors in fast passages to be detected. Such errors may be difficult to identify when heard at the original speed, due to human perceptual limitations. The nature of these limitations and their adverse effects on piano playing are outlined in Section 6.4.

The usual way to establish the benefits of a new teaching aid is to make controlled experiments (cf. Hammer, 1963). That is, a "test" group of students is taught using the aid, while a "control" group receives normal instruction. Any significant differences between the results of the two groups are then used to evaluate the aid. However, before such an experiment can be designed, the benefits that are expected from the aid must be formulated, so that the experimental procedures can be arranged to highlight them. This chapter examines the benefits to pianists that are likely to accrue from the use of the new computerized aid. Evidence from treatises on piano playing and standard psychology texts is presented in support of these expectations. Informal experiments are described which illustrate benefits of the aid in teaching piano techniques, and in analysing virtuoso performances. It is left to future researchers to design and carry out the controlled experiments needed to vindicate the benefits that are explained, supported and illustrated here. However, the whole business of a controlled experiment in an artistic field is fraught with difficulty. For example, it may be difficult to understand what is meant by the 55.2 percent average
improvement in instrumental performance reported by Diehl and Ziegler (1973) for their computer based teaching program.

The next section summarizes the benefits and drawbacks of the devices currently available to pianists. How the computer can help overcome some of these drawbacks is mentioned. Then in Section 6.3, the computerized aid is described. It is pointed out that very little prior knowledge about computers is needed to operate it. Section 6.4 presents the main argument of this chapter, showing how established psychological principles apply to piano performance. Factors affecting the learning of skills are outlined. It is explained how the augmented feedback provided by the computerized aid can reduce the time needed to learn some of the muscular and perceptual skills required for piano playing. Also, by magnifying errors in rhythm and articulation, the aid enables pianists to increase the precision of their playing. Applications of the computerized aid to aspects of piano playing are discussed in Section 6.5 in which it is concluded that the aid is likely to help students learn scales and arpeggios, as well as pieces and studies, but is unlikely to be any use with sight reading. It is also concluded that the feedback provided via the computer complements that offered by existing aids.

Section 6.6 presents an account of preliminary experiments in the use of the computer for teaching a variety of piano skills. In Section 6.7, the extension of the computerized aid to apply to instruments other than the piano is proposed. Improvements to the existing piano teaching aid are also suggested. The findings of this chapter are summarized in Section 6.8. Finally by way of indicating the likely reactions of pianists to the new aid, Section 6.9 describes an impromptu encounter (cf. Lamb, 1977b, 1978) between international concert pianist Andre Tchaikovsky and the computerized aid, in which many of the ideas put forward in this chapter are highlighted. Andre Tchaikovsky's remarks support the main findings of this chapter, namely that the computer has considerable potential as a performance teaching aid, and that the benefits it offers pianists are quite different from those provided by existing aids.

6.2. BENEFITS AND DISADVANTAGES OF EXISTING AIDS.

The devices currently available to pianists are summarized in Table 6.1. They all provide information about piano playing - the metronome and practice clavier during a performance; the recording devices, afterwards. However, pianists can rarely pay attention to every detail of their playing (cf. Kochevitsky, 1967, p 50; see also Section 6.4.3 for a discussion of some limits of human attention). This restricts the effectiveness of the metronome and affects the usefulness of the practice clavier and recording devices, as is now explained.

The metronome is a device which injects regularly spaced clicks into the musical sounds produced when playing. The performer must cope with this extra auditory information, perceiving any failure
to keep in time with the clicks and adapting the playing speed so as to stay in synchronization with the metronome. If the player is already fully occupied, the attention required for adjusting to the metronome must be diverted from some other area of concentration (e.g. finding the correct notes). This possibly explains why this device can at times be more of a hindrance than a help to beginners. The metronome's particular benefit lies in its provision of an objective reference time-scale, thereby enabling pianists to come to terms with fluctuations in their subjective estimation of time (an explanation for fluctuations in subjective time estimation is given by Riess-Jones, 1976).

The practice clavier functions by eliminating the sound of the music, substituting instead clicks at the beginning and/or end of notes (the operation of this device is explained in Section 2.2). It thereby allows the pianist to concentrate solely on the synchronization of notes and chords and on the cessation of notes (these "cutoffs" are often difficult to hear in a piano performance, as is pointed out in Section 6.6). However, so much information about a performance is eliminated that the practice clavier is little used.

Both the audio tape recorder and the videotape recorder allow a performance to be observed and analysed many times. For example, tone quality, rhythmic accuracy, and dynamics (i.e. "louids and softs") may be examined, each during a separate playback of the audio tape; posture, muscle relaxation and fingering may be scrutinized during different videotape reruns. Both devices enable a performance to be perceived by the player from the vantage point of an audience. They thereby offer an indication of how well the music "projects" and of what extraneous things the audience sees (e.g. grimaces) and hears (e.g. grunts and foot tapping). A major drawback with both these aids is the amount of time wasted in rewinding, scanning and positioning to specific places in the recorded performance. Furthermore, an event can only be examined for the duration of its replay/screening. Thus,
because of limits to human attention (as outlined in (a) and (c) in Section 6.4.3), some rapid or complicated passages cannot be examined in detail in the course of a single replay. A way around this is to use a recording device which also functions in slow motion (e.g. some video recorders, which may also "freeze" a movement - see Section 2.2). However, because of the accompanying drop in pitch and loss of sound quality, the tape recorder is unsuitable for slowed-down playback of musical sounds. With the computerized aid described in Section 6.3 music may be played back at any speed (without a change in pitch) and there are no delays due to rewinding. The main benefit of recording devices is that they facilitate the examination of aspects (e.g. pedalling) that the pianist may be too busy to concentrate on while playing, and which may not be repeatable.

A very different source of augmented feedback is the human piano teacher. As well as providing encouragement and personal interaction, the teacher can offer judgement and constructive criticism, none of which can be supplied by the above devices. In fact, the four mechanical aids discussed above require to be used with judgement in order to be beneficial. They enable criticism to be made (either by teacher or student) - they cannot criticize or analyse by themselves.

The computerized aid described in the next section can analyse the playing of cross-rhythms. Its main use (as reported here) is to provide slowed-down playback and a special visual display of a pianist's performance, thereby enabling either teacher or student to analyse what was played. As well as revealing phonic details that cannot be detected by using the tape recorder (for reasons given in Section 6.4.3) the computerized aid enables faults in hand position to be deduced that cannot easily be detected by non-slowed video techniques (as explained in Section 6.5 and illustrated in Section 6.6). Unlike the metronome and practice clavier, the computerized aid does not provide feedback during playing. It provides delayed feedback, as do the recording devices discussed earlier. However, in an improvement on these recording devices, the computerized aid requires little time for scanning and positioning (as is explained in the next section). Singer (1975) has shown that for the learning of muscular skills, the shorter the delay between performance and receiving feedback, the better. Thus, when teaching muscular skills with the aid of the computer (or with the recording devices discussed earlier) it is better to work with short musical extracts, in order to keep this delay to a minimum.

Section 6.5 explains that there is much that the computerized aid does not show about piano playing (e.g. loudness and tone quality). Nevertheless, it can provide different feedback from that offered by existing aids, and in some cases complements what they provide.
6.3. OPERATION OF THE COMPUTERIZED AID.

The computerized aid for musicians developed by Tucker et al (1977) is described in Section 3.3. Part of this system is a music typesetting aid with which music may be displayed, either in conventional notation or in a modern notation of a kind used by some contemporary composers (cf. Brown, 1959). With the latter notation (which is referred to as MOD - short for "modern") each note is represented by a rectangular block, positioned on the conventional stave (see Figure 6.1). Duration and pitch are indicated by this block's length and vertical position, respectively. There are no rests or accidentals - a black note is represented by a block whose vertical position lies midway between those used conventionally. An example of MOD notation is given in Figure 6.1. Since the MOD display is isomorphic, in both a temporal and a pitch sense, to the music it is representing (unlike conventional music notation with its essentially discrete, parametric representation of note durations) it is ideally suited to performance oriented tasks e.g. the analysis of piano playing. In addition, the MOD display seems to be a "compatible" (i.e. "natural") way of representing musical performance (compatibility is explained by Annet and Roth, 1974, p.81).

FIGURE 6.1 "MOD" display of C chromatic scale in minor thirds played rapidly with the right hand only. Faulty changes in hand position (at the places marked *) are easily recognized from the undesirable breaks in what should be a smooth, unbroken line. (In this notation, black notes are represented by blocks whose vertical position lie midway between those used in conventional notation.)
A comprehensive account of the operator commands (for the musicianship aids system) is given by Tucker (1977) and so only the relevant procedures are outlined here. Table 6.2 summarizes those operator commands that may be typed on the console typewriter when teaching or analysing piano playing techniques. Response times for most commands are less than a second, and the time taken to display a page of MOD notation is about three seconds. As explained in Section 3.3, the depressing of a key on the organ keyboard causes the corresponding electronic organ note to be sounded.

**COMPUTER COMMANDS DURING PIANOFORTE INSTRUCTION**

<table>
<thead>
<tr>
<th>Command</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Record music played on the organ keyboard</td>
</tr>
<tr>
<td>S</td>
<td>Display music in MOD notation, starting at page 1</td>
</tr>
<tr>
<td>S,n</td>
<td>Display page n in MOD notation</td>
</tr>
<tr>
<td>N</td>
<td>Display next page</td>
</tr>
<tr>
<td>P</td>
<td>Playback, starting from the beginning</td>
</tr>
<tr>
<td>P,n</td>
<td>&quot; &quot; page n.</td>
</tr>
<tr>
<td>V,n or V,n.m or V,.m</td>
<td>Speed up playback by a factor of n or n.m or .m</td>
</tr>
<tr>
<td>V,R</td>
<td>Reset playback speed to the original speed</td>
</tr>
<tr>
<td>T,+n or T,-n</td>
<td>Transpose by +n (or -n) semitones (this command applies to both display and playback)</td>
</tr>
<tr>
<td>T,R</td>
<td>Reset transposition factor to zero</td>
</tr>
<tr>
<td>I</td>
<td>Insert a note or chord. The start and end position are indicated on the MOD display using the &quot;joystick&quot; cursor. Then the new note(s) are played.</td>
</tr>
<tr>
<td>O</td>
<td>Record, sound-on-sound (overlay). The simultaneous playback and record is preceded by 3 beeps at 1 second intervals.</td>
</tr>
<tr>
<td>O,n</td>
<td>Overlay, starting from page n</td>
</tr>
<tr>
<td>D</td>
<td>Delete a note or chord. The start of the offending note(s) is indicated on the MOD display by using the &quot;joystick&quot; cursor.</td>
</tr>
<tr>
<td>L</td>
<td>Analyse the performance of cross-rhythms</td>
</tr>
<tr>
<td>F,name</td>
<td>Store the music in a file called &quot;name&quot;</td>
</tr>
<tr>
<td>G,name</td>
<td>Get the file called &quot;name&quot; and replace the present music with the contents of the file.</td>
</tr>
</tbody>
</table>

**TABLE 6.2** A summary of the commands available for providing feedback relating to piano playing, and to aid the instruction of piano performance techniques.

A computer program which analyses the playing of cross rhythms is activated by typing the command "L" (see Table 6.2). This program indicates which notes of a regular, i.e. periodic, cross rhythm are incorrect, and gives the extent of each (periodic) error expressed as a percentage of the "period" of the cross rhythm. The type of performance that can be analysed in this way
comprises any "m against n" cross rhythm (where m and n are integers less than 20) played on the organ keyboard. The performer must begin at the start of a cross-rhythm "period" and play one note for each element of the rhythm.

The application of the commands listed in Table 6.2 to piano performance is illustrated by the following two hypothetical examples:

HYPOTHETICAL EXAMPLE 1: PRACTICE: A student types "R" on the console typewriter and then plays a piece by Bartok on the organ keyboard. To check for mistakes "P" is typed, which causes the performance to be played back. Suppose that in one place the rhythm sounds rather unsteady, but the reason for this is not obvious. The student finds the place where the mistake occurred by typing "S,2," for example, and then "N" after which the place is located on page 3 of the MOD display. Then, the typing of "V,.2" followed by "P,3" enables the student to hear the unsteady rhythm played back at one-fifth of the original speed while following the corresponding MOD notation on the screen. The MOD notation might indicate that the unsteady rhythm was partly due to some notes being held on too long. The slowed down playback might show that some notes were being rushed, thereby causing further unsteadiness. Having identified the above errors, our hypothetical student would then resort to special practice to correct them.

HYPOTHETICAL EXAMPLE 2: TEACHING: In preparation for a class discussion on interpretation, the instructor types "R" and plays a very romantic piece by Schumann on the organ keyboard, with appropriate rubato (i.e., rhythm fluctuations of a desirable nature). An inadvertent wrong note is corrected by electronically pointing to it (see Section 3.3.3), and typing "C,P" after which the right note is played on the organ keyboard. The command "F,DEMO" (see Table 6.2) causes the corrected example to be filed away inside the computer. Several hours elapse, during which the computerized musicianship teaching aid may be used for a variety of purposes (e.g., aural training or harmony assessment — see Chapters 3 and 4). Then, when the piano class arrives for their discussion on interpretation, the instructor types "G,DEMO" followed by "V,5" and "P" which would cause the Schumann example (recorded earlier) to be played back at half speed. This might be used to demonstrate the way in which rubato is used in the interpretation of Romantic music — i.e., showing the tempo fluctuations that are desirable as opposed to those that are not.

The above two examples indicate the manner in which the computerized aid is operated. The way in which it can be used to overcome pianists' perceptual limitations is explained in the next section, after which its applications to piano playing techniques are discussed.

Two useful features of the aid described in this section are its immediacy of response to operator commands, and its ease of operation — no special knowledge about computers is required in order to use the aid.
6.4. THE LEARNING OF SKILLS

The skills required for piano playing may be divided into perceptual-motor skills (i.e. muscular and perceptual skills) and language skills. The latter involve the manipulation of signs and symbols, and also deal with the evocation of "mood". This chapter is concerned mainly with the acquisition of perceptual-motor skills and only touches on those language skills (e.g. phrasing) which are directly linked with the former. Chapters 3 and 4 deal with the use of the computer in the teaching of language skills relating to chords, keys, etc. (in the fields of aural training and composition, respectively).

In general (cf. Fitts and Posner, 1967, p.11) the learning of a skill passes through three stages (transitions between stages may be indistinct):

a. Understanding the skill: during this stage explanations and demonstrations may help the student realize what is required. A "trial and error" approach by the student may lead to an awareness of the problems involved.

b. Practice: ideas gained in (a) are used in making the components of the skill habitual. These components are practised separately (e.g. finger co-ordination, maintenance of a good hand position, and the production of a uniform tone are components of trilling skills - cf. Kochevitsky, 1963, p.40).

c. Making the skill autonomous: the skill is practised in its entirety, becoming automatic and less subject to conscious control. Performance of the skill continues to improve with practice, even when it is not consciously attended to.

The computerized aid described in Section 6.3 can help with (a) above, by enabling stored examples of virtuoso performances to be replayed so as to illustrate particular skills (e.g. playing an Alberti Bass, trilling). Such examples may be analysed using the MOD display and the slowed-down playback facility (described in Section 6.3) in order to show the student exactly what is involved. During stage (b) above, the MOD, slowed-down playback, and cross-rhythm analysis facilities can help by providing feedback about the student's playing. The benefits available are explained in Sections 6.4.2 and 6.4.4. With stage (c), the computerized aid can reveal errors in the autonomous performance of a skill, that the student is unaware of. The manner in which this is achieved is explained in Section 6.4.4 and illustrated in Section 6.6.

Thus the computerized aid can help with all three stages of learning. The exact nature of the benefits offered and the ways
in which they differ from the benefits provided by existing aids, are discussed in the following sections.

6.4.2. TECHNIQUES FOR IMPROVING LEARNING.

6.4.2.1. MAGNIFICATION OF ERRORS.

All the perceptual-motor skills needed for piano playing require a high degree of precision. The precision of a response (e.g. the playing of a note) is limited by the accuracy of the feedback information (e.g. how loud the note sounds) (cf. Fitts and Posner, 1967, p.73). Helson (1964) has shown that magnification of the error in a task involving fine adjustments can improve performance.

Slowed-down playback magnifies errors in synchronization and timing errors in rhythm. MOD display can be used in conjunction with slowed-down playback (i.e. the time scale of the MOD display is expanded) to magnify errors in duration and errors in the timing of cutoffs. As a result, the computerized aid can help improve the precision of a student's rhythm, synchronization and articulation. Examples of such improvements are reported in the experimental results presented in Section 6.6.

To date, the computerized aid seems to be the only musicianship aid to provide either MOD display or slowed-down audio playback (existing aids are summarized in Chapter 2 - see also Section 6.2). The tape recorder is unsuitable for providing slowed-down playback because of the resulting drop in pitch and deterioration in sound quality.

6.4.2.2. USE OF AUGMENTED FEEDBACK

The term "feedback" refers to the information arising as a consequence of a person's action(s) (cf. Fitts and Posner, 1967, p.28). This may be divided into two types: "intrinsic feedback", which is a natural consequence of the action itself (e.g. kinesthetic cues arising from a hand movement), and "augmented feedback," which arises from external or artificial cues from the environment.

The rate of learning can be increased by the use of augmented feedback (cf. Fitts and Posner, 1967, p.28). This may be due to the augmented feedback providing

(i) knowledge about the performance of the skill,
(ii) increased motivation and
(iii) reinforcement (i.e. the correct actions "sink in" more).

It has been shown (cf Smode, 1958) that the improvement in performance resulting from the use of augmented feedback continues even after conditions are returned to normal (i.e. when the augmented feedback is absent).

All the aids listed in Table 6.1 provide augmented feedback since
they are external to the pianist. When used appropriately (e.g. during the learning of the skills listed next to each device in Table 6.1) they are able to provide (i) (ii) and (iii) above, thereby permitting the student to learn more quickly.

6.4.3. HUMAN MUSCULAR AND PERCEPTUAL LIMITATIONS.

The rate of learning a skill and the proficiency attained are subject to limitations imposed by the human musculature and nervous system. In particular, limitations of this nature that affect the learning of piano performance may be summarized as follows:

a. it is difficult to attend to more than one sensory source (e.g. eyes, ears) at a time (cf. Fitts and Posner, 1967, p.56);

b. the perception of relatively simple data is limited to about ten items per second (cf. Fitts and Posner, 1967, p.78);

c. the maximum rate of response is also limited to about ten items (or "chunks" - these are explained below) per second (cf. Fitts and Posner, 1967, p.78);

d. the maximum rate of repetitive movement is limited to about ten per second (cf. Fitts and Posner, 1967, p.78);

e. with a continuous task, error corrections are limited to two per second (cf. Craik, 1948);

f. hand and eye can track at up to five movements per second (cf. Fitts and Posner, 1967, p.78);

g. the reaction time for hand and foot moves lies between 140 and 180 milliseconds (cf. Fitts and Posner, 1967, p.74);

h. when responses are required for two successive stimuli, the second response has a longer than usual reaction time (called the "psychological refractory period") which decreases as the interval between the signals increases (cf. Fitts and Posner, 1967, p.80). This phenomenon occurs even when one signal is visual and the other auditory, and when the responses are in opposite hands. It also occurs when the subject expects the stimuli to occur in rapid succession (cf. Welford, 1952).

The limitations summarized above mainly apply to the first two stages in the learning of skills (as described in Section 6.4.1). The following consequences of these limitations are mostly taken from the author's own piano playing and teaching experience: As a result of (a) (above) it is easier to concentrate on tone production when playing from memory. It is partly due to (b) that
individual wrong notes occurring in a performance of a Mozart composition are much more easily detected than those occurring in a composition by Liszt (with its many more notes per second). According to Kochevitsky (1967), "for exceedingly rapid scale playing (in the finale of Chopin's G Minor Ballade, for example), we should unite seven notes in one will-impulse ... Thus at each strong beat we send a will-impulse and are not conscious of the notes which are played between these strong beats". The necessity for this uniting of many notes into a single will-impulse (referred to later as "chunking") follows from (c) above. As a result of (d) rapid repetitions of a single note (cf. Liszt, 1860) can be played much faster using changing fingers than with the same finger all the time. Because of (e) and (f) it is advisable to practise large leaps slowly, and it helps to watch one's hands. Limitation (g) implies that it is much more difficult to correct wrong notes while playing fast passages than during slow passages. Finally, as a consequence of (h), two mistakes made at the same time cannot be corrected simultaneously.

The next section discusses ways in which the computerized aid can help pianists cope with limitations (a), (b) and (c), above. But first, a little needs to be said about chunking.

Joseph Lhevinne in a recorded performance of Strauss's "Blue Danube" (arr. Schultz-Evler) plays on average 19 notes in every second (cf. Gueroult, 1966). Still more is required of the pianist who plays all 1441 notes of Chopin's "Minute Waltz" in sixty seconds - an average of 24 notes per second! Clearly, the rate of note output is higher than the 10 items per second limit set by (c). Thus, chunking - the uniting of several actions in a single will-impulse - must be taking place. Similarly, the person listening to the above performances (since he does not perceive gaps in the music) must also be chunking - by uniting stimuli. This phenomenon is cogently explained by Boynton (1961) who describes visual chunking as "temporal quantization of the visual input by the higher visual nervous system, so that the input is "packaged" into discrete time frames within which a purely temporal discrimination is not possible". The aspect of chunking that most inconveniences piano practice is the restriction that chunks cannot be analysed into their component parts, in the central nervous system. An important consequence of this restriction is that when chunking takes place, it is possible to notice the existence of an error (i.e. that a "chunk" is wrong) without being able to identify the error itself exactly.

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6.4.4. **COPING WITH HUMAN LIMITATIONS.**

Slowed-down playback and MOD display can (it is shown in Section 6.6) help pianists overcome the difficulty of attending to several sensory sources at once (limitation (a) in Section 6.4.3). By providing information about aspects of playing (e.g. rhythm and articulation) that the performer is not attending to, MOD and slowed-down playback can reveal errors that he (or she) is unaware of. For example, Section 6.6 describes how a student, while concentrating on playing the correct notes and trying to evoke a suitable mood, made serious errors in his legato playing that he did not notice until he saw the MOD display (it is most unlikely that this particular error would have been noticed as a result of using a recording device, since the teacher, who was present, did not notice it).

Limitations (b) and (c) in section 6.4.3 involve chunking, as is explained in the preceding section. For the reasons given there, it is not possible for an unaided human to analyse the contents of a chunk. However, by respectively slowing down, "freezing," and analysing aspects of a performance; slowed-down playback, MOD display and the cross-rhythm analysis facility (described in Section 6.3) enable perceptual and motor chunks to be analysed. In this way, pianists can progress from merely being aware of the existence of an error, to actually identifying it. It is explained in Section 6.5 and demonstrated in Section 6.6 how such analysis is used to improve pianists' articulation, rhythm, and playing of ornaments.

In the above ways, the computerized aid can help pianists overcome some of their perceptual limitations. It achieves this by providing facilities not available with existing aids.
Aspects of piano playing are now considered, in order to determine which skills can benefit from the computerized aid described in Section 6.3. An internationally recognized system of examinations (T.C.L., 1976) divides piano playing into the following categories: (1) scales and arpeggios, (2) sight reading, and (3) pieces and studies. These three categories are now discussed in the light of what the computerized aid has to offer.

6.5.1. SCALES AND ARPEGGIOS

Table 6.3 summarizes the skills which are generally regarded as being required in order to play scales and arpeggios properly. Also shown are the aids that can provide feedback relating to those skills. When one hand is playing 8 notes a second (a comfortable speed, in the author’s opinion), passing the thumb under takes between one-quarter and one-half second (i.e. 2 to 4 note durations). During this manoeuvre, which is crucial to scale

<table>
<thead>
<tr>
<th>TECHNICAL ASPECTS OF SCALES AND ARPEGGIOS</th>
<th>APPROPRIATE FEEDBACK AIDS:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Computerized</td>
</tr>
<tr>
<td>Rhythmic precision</td>
<td>SPB</td>
</tr>
<tr>
<td>Synchronization of hands</td>
<td>SPB</td>
</tr>
<tr>
<td>Smooth passage of the thumb</td>
<td>MOD</td>
</tr>
<tr>
<td>Playing the correct notes</td>
<td>SPB,MOD</td>
</tr>
<tr>
<td>Production of an even tone, with</td>
<td>-</td>
</tr>
<tr>
<td>appropriate accents</td>
<td></td>
</tr>
<tr>
<td>Use of correct fingering</td>
<td>-</td>
</tr>
<tr>
<td>Maintenance of a good posture and hand</td>
<td>-</td>
</tr>
<tr>
<td>position</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 6.3 Technical skills acquired when learning to play scales and arpeggios. The computer can help detect faults that occur too rapidly to be observed with non-computerized aids. (MOD = MOD display, SPB = slowed-down playback, tape = tape recorder, video = videotape recorder or CCTV)
and arpeggio playing, "all twisting of the hand must be strictly suppressed" and "the thumb must already stand over its key at the instant when the preceding finger strikes" (Kullak, 1893, pp.140 and 59). Gat's (1968) photographs indicate that slowed-down video playback may show up twisting, but in his photographs the hand hides the thumb while the latter is being passed under. The computerized aid, however, enables faults in thumb positioning to be deduced from timing errors revealed by the MOD display of the manoeuvre (see Figure 6.1). By magnifying synchronization errors and timing errors in rhythm, slowed-down playback can help improve the precision of a pianist's synchronization and rhythm, as explained in Section 6.4.2.1. Such magnification is also available from slowed-down video, provided that the fingers' striking is clearly visible (this is not always the case when the thumb is passed under, as explained above).

Any wrong notes may be detected in a few glances using the MOD display. For the beginner student, they may be made embarrassingly obvious by using slowed-down playback.

In the above ways the computerized aid can help pianists play scales and arpeggios more precisely.

6.5.2. SIGHT READING

According to Plaidy (1853) "The main aim in practising sight reading is to play ... the piece through from beginning to end, without allowing oneself to be stopped by any difficulty. Although many imperfect chords and indistinct passages may occur, and although he may leave out many notes, yet the player must not be delayed by them and stop to correct himself, but play on uninterruptedly and endeavour to give such a rendering as may be, in the main, a faithful picture of the whole work." Aspects of piano playing involved in producing such a "faithful picture" are summarized by the author in Table 6.4 (cf. Last, 1956; see also Plaidy, 1853).

Aspects (i), (ii) and (iv) (of Table 6.4) use the "running short term memory" i.e. the short term memory that is used for "storing a sequence of stimuli before starting to respond to them" (Fitts and Posner, 1967, p. 72). "Running short term memory ... is one of the most important factors in limiting skilled performance ... In cases where the natural language is used, it is clear that subjects are grouping or recoding stimuli into chunks on the basis of their familiarity with the material of the task" (Fitts and Posner, 1967, p.73). Since music may be regarded as a natural language (for the reasons given by Winograd, 1968), it seems that sight reading is designed to train the running short term memory and to develop the language skills (i.e. those involved in manipulating signs and symbols) involved in chunking the visual music input.
Since the overall impression is what matters in sight reading (cf. Plaidy, 1853) some tempo fluctuations and asynchronism are allowed. Thus the metronome and practice clavier are unsuitable here. Neither the computerized aid nor any of the recording devices can provide feedback about the running short term memory or about the way in which the visual input is chunked. Thus, the aids shown in Table 6.4 can only provide the pianist with the end product in which to find symptoms (e.g. missing notes) from which errors (e.g. in chunking) may be diagnosed.

Therefore, none of the aids listed in Table 6.1 is likely to help significantly with sight reading. The Tachistoscope (see Section 2.2) can help pianists develop aspect (i) of Table 6.4 (i.e. "Taking in entire chords and phrases at a glance") by increasing the amount of information taken in at a glance. The use of a screen between hands and eyes during practice can help with aspect (iii) by developing the use of non-visual proprioceptive feedback to control the hands.

6.5.3. PIECES AND STUDIES

A pianoforte study (or étude) is usually a composition whose thematic material is restricted to one type of passage so that a particular technical difficulty is presented throughout, in various forms (cf. Scholes, 1950, p. 299). Table 6.5 summarizes the technical difficulties focussed on by a number of studies by Czerny (1839), Chopin (1829), Liszt (1852), Bartok (1956) and Debussy (1916). The purpose for which pianoforte studies are composed is generally accepted as being the following (see for example Plaidy, 1853, p.3). A pianist cannot perform compositions with feeling and taste while contending with mechanical difficulties. The object of studies is to help pianists acquire
the technical skills required for the proper performance of pieces. Thus, in general, the particular skills focussed on by studies are a subset of those required for playing pieces. In the following section the skills in this subset that are summarized in Table 6.5 are discussed in the light of the computerized aid, after which the remaining skills of piano playing are considered.

<table>
<thead>
<tr>
<th>MUSCULAR SKILLS FOR PIANISTS</th>
<th>SUITABLE FEEDBACK AIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) trills &amp; other fast embellishments</td>
<td>MOD, SPB</td>
</tr>
<tr>
<td>(2) complicated cross-rhythms</td>
<td>XRA, SPB</td>
</tr>
<tr>
<td>(3) legato and staccato</td>
<td>MOD, tape</td>
</tr>
<tr>
<td>(4) velocity playing</td>
<td>SPB</td>
</tr>
<tr>
<td>(5) leaping</td>
<td>video</td>
</tr>
<tr>
<td>(6) dynamic contrasts</td>
<td>tape</td>
</tr>
<tr>
<td>(7) production of different tone-colours</td>
<td>tape</td>
</tr>
<tr>
<td>(8) passing the thumb under</td>
<td>MOD, video</td>
</tr>
<tr>
<td>(9) octave-playing techniques</td>
<td>MOD, SPB, video</td>
</tr>
<tr>
<td>(10) rotation and pivoting</td>
<td>video</td>
</tr>
<tr>
<td>(11) rhythm precision</td>
<td>SPB, metronome</td>
</tr>
<tr>
<td>(12) crossing-over the hands</td>
<td>video</td>
</tr>
<tr>
<td>(13) fast, repeated notes</td>
<td>SPB, MOD, tape</td>
</tr>
</tbody>
</table>

TABLE 6.5 Some of the technical skills required by the advanced keyboard performer. The computerized aid can provide feedback relating to many of these skills (the abbreviations are explained in Table 4.3).

6.5.3.1. TECHNICAL SKILLS

Bach (1753) considers trills to be "the most difficult embellishments", liable to "bleat or grow ragged" if played incorrectly. With 12, 20 and 30 notes per second considered comfortable rates (in the author's opinion) for single, double and triple trills respectively, it is not usually possible to attend to every note of a trill. This is because human perception is limited to about ten items per second as explained in Section 6.4.3. Used together, MOD and slowed-down playback "magnify" details of timing and duration, making apparent any unevenness in
the rhythm (evenness is considered by Bach, 1753, to be a desideratum of good trilling). Sections 6.6 and 6.9.1 demonstrate how this magnification is used to improve the playing of single and triple trills. (The reasons for the improvement are outlined in Section 6.4.2).

An analysis of the playing of cross rhythms is available from the cross-rhythm analysis facility. Performance can be improved by the use of this feedback, as explained in Section 6.4.4. Similarly, the feedback provided by MOD about legato and staccato playing can improve a pianist's competence at skills (3) and (9) of Table 6.5.

In velocity playing, rate of note production can often exceed 1 per second (cf Gueroult, 1966). For the reasons given in Sections 6.4.3 and 6.4.4 slowed-down playback enables mistakes (e.g. wrong notes) in such fast playing to be detected much more easily than with other aids. Slowed-down playback also helps pianists play rhythms more precisely (as explained in Section 6.4.2), which is useful when acquiring skills (2), (4), (9), (11) and (13) of Table 6.5.

MOD display is especially useful in showing up errors in passing the thumb under, as is explained in Section 6.5.1 and illustrated in Figure 6.1.

In the above ways the computerized aid can help a pianist acquire over half the skills listed in Table 6.5. Shortly, Section 6.6 presents examples in which the computerized aid is used in the teaching of skills (1), (2), (3), (9) and (11) (of Table 6.5).

6.5.3.2. INTERPRETATIVE SKILLS

In addition to technical skills (e.g. those described in the preceding section), pianists use skills relating to interpretation (or expression). Interpretation may be described as supplying "that part of the music which the composer was not able to put into writing" and which therefore must be provided by the performer "out of his own musical sense and his emotion" (Scholes, 1950, p.301). In doing so, the performer may change the durations and timing of "certain purposeful violations of the beat are often exceptionally beautiful" (Bach, 1753, p.150).

According to Bach (1753), "As a means of learning the essentials of good performance it is essential to listen to accomplished musicians". More recently, Gagne (1977, p.227) outlines the benefits of teaching by example. The computerized aid can help by storing performances of accomplished musicians, which may be played back and analysed using MOD and slowed-down playback. Such analyses can show up the kinds of "deviations" that are desirable (e.g. the "purposeful violations of the beat" mentioned above). Similarly, the computerized aid enables teachers to point out those deviations in a student's performance that are "out of style". Other aids also show up deviations, as is indicated in Table 6.6, but only the computerized aid and slowed-down video
"magnify" details, thereby enabling subtleties to be brought out into the open.

### ELEMENTS OF MUSICAL INTERPRETATION

<table>
<thead>
<tr>
<th>ELEMENTS OF MUSICAL INTERPRETATION</th>
<th>PARAMETERS INVOLVED</th>
<th>SUITABLE FEEDBACK AIDS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rhythm</td>
<td>timing</td>
<td>SPB,XRA metronome, tape</td>
</tr>
<tr>
<td>Notes</td>
<td>pitch,duration</td>
<td>MOD,SPB tape</td>
</tr>
<tr>
<td>Dynamics</td>
<td>loudness</td>
<td>- tape</td>
</tr>
<tr>
<td>Tempo</td>
<td>timing</td>
<td>PB tape</td>
</tr>
<tr>
<td>Articulation</td>
<td>duration,loudness</td>
<td>MOD tape</td>
</tr>
<tr>
<td>Pedalling</td>
<td>overall sound</td>
<td>tape, video</td>
</tr>
<tr>
<td>Tone</td>
<td>overall sound</td>
<td>tape</td>
</tr>
<tr>
<td>Accents</td>
<td>loudness</td>
<td>tape</td>
</tr>
<tr>
<td>Phrasing</td>
<td>timing,loudness</td>
<td>SPB tape</td>
</tr>
<tr>
<td>Rubato</td>
<td>timing</td>
<td>PB tape</td>
</tr>
<tr>
<td>Ornamentation</td>
<td>pitch,duration</td>
<td>MOD,SPB tape</td>
</tr>
<tr>
<td>Posture</td>
<td></td>
<td>video</td>
</tr>
</tbody>
</table>

**TABLE 6.6** The elements of piano playing that are combined by the performer to make up an "interpretation" of a piece of music. Collectively they determine the mood of the performance. They should be chosen so as to be consistent with the musical style of the composition being performed. (The abbreviations are explained in Tables 6.3 and 6.4.)

The elements of music which the performer has licence to change, to a greater or lesser degree, are summarized by the author in Table 6.6 (cf. Bach, 1753; Kullak, 1893; and Scholes, 1950). The limit to which liberties may be taken is determined by the style of the piece (cf. Gat, 1968).

Last but not least, "A musician cannot move others unless he too is moved" (Bach, 1753, p.13). Obviously, none of the aids listed in Table 6.1 can help a pianist be moved.

Thus the computerized aid can provide feedback about a limited number of points of style and interpretation. Examples of the use of the aid with some of these points (e.g. rubato, ornamentation) are given in Section 6.6 and in the informal analysis of André Tchaikovsky's playing, presented in Section 6.9.
6.6. EXAMPLES OF TEACHING WITH THE COMPUTERIZED AID

After the preceding theoretical discussion, this section illustrates some practical applications of the computerized aid for teaching piano techniques. The incidents described are taken from experimental computer-aided lessons with five students (identified by the initials of their first names - C, H, J, M and W), which took place during the period 1975 - 1977. For brevity, the operator commands (cf. Section 6.3), which were typed by the author on the console typewriter, are not reported here;

MENDELSSOHN’S SONG WITHOUT WORDS

J, a schoolboy, had been learning the piano for five years when he began work on a "Song Without Words" by Mendelssohn. Despite weeks of practice his playing of the piece sounded dull and uninspired, and so a session with the computerized aid was tried, in an attempt to find reasons for the dullness. When J played the first page on the organ keyboard, the resulting MOD display contained a large splodge where a clearly articulated turn - vital to the mood of the music - should have been indicated. This is illustrated in Figure 6.2. Subsequent playback of the passage at one-third speed showed J that although the correct notes were being depressed, they were not being released until much too late. J then practised the offending turn several times to try and eliminate this dissonant blurring. However, the MOD display of the practised version indicated little, if any, improvement. Further unsuccessful attempts led us to realise that the reason for the error lay in a muscular weakness in his 3rd, 4th and 5th fingers. Remedial exercises for strengthening these fingers resulted, a few weeks later, in much clearer turns and increased vitality in J’s playing of the piece.

CROSS RHYTHMS

On another occasion, J, who had been thoroughly practising examples of "2 against 3" and "3 against 4" rhythms, was taken to the computerized aid to find where his faults in playing these cross-rhythms lay. J and the author were aware of rhythm errors but could not pinpoint them exactly. When J played an example of 2 against 3 on the organ keyboard, the cross-rhythm analysis program (described in Section 6.3) indicated a total timing error of 7% and that the second note of the duplet was being played too soon. After a little practice, J’s next attempt was 5% in error - the second duplet note was now a little late. With further practice J reduced his error to 3% - corresponding to a competent performance, in the author’s opinion.
FIGURE 6.2 The MOD display of J's attempt at the Mendelssohn "Song Without Words". The splodge in the right hand at the start of the second line indicates an error, as is explained in the text.
PITCH CONCEPTS

The next student, C, aged seven, had only been learning the piano for a few weeks, during which time she had been playing simple tunes by ear. When it was time for her to be introduced to music notation she was given a lesson with the computerized aid. The object of this lesson was to use MOD display to reinforce concepts of "up" and "down" with respect to pitch, and to show how rising and falling sounds can be represented visually. The author and C played tunes on the organ keyboard that C had already learned, and we followed the MOD display during playback by pointing to the blocks representing the sounds. Then with prompting, C played clusters of high and low notes on the organ keyboard and saw what they "looked like" on the MOD display. After some experimenting she worked out the glissandi required to "draw" the "seagulls" illustrated in Figure 6.3.

![Figure 6.3](image)

FIGURE 6.3 After experimenting with the computer's organ keyboard, 7 year old C played the falling and rising pitches to "draw" these "seagulls" using the MOD display.

MOONLIGHT SONATA

A much more advanced student is H, who has a diploma in piano performance (L.R.S.M. - a qualification comparable in terms of performance, with a Batchelor's degree in piano performance). When studying Beethoven's Moonlight Sonata with the author, two problems of interpretation arose - one dealing with legato playing, the other involving rhythm. Although H was playing the correct notes at the beginning of the first movement, he was failing to evoke the calm mood necessary at the opening (see Kullak, 1893, pp. 324 - 327 for a fascinating account of different interpretations of this sonata, including that of Ulibischeff, who seems to have been the first to associate moonlight with this work). When this passage was played by H on the organ keyboard, the resulting MOD display revealed large gaps between the melody notes (see Figure 6.4a), and smaller breaks between the octaves in the bass. Instead of joining the notes...
with his fingers, H had relied on the sustaining pedal to bridge the gaps. As a result, he was not achieving the calm flowing legato indicated by the composer (cf. Craxton and Tovey, 1931, p. 54) and exemplified by Andre Tchaikovsky's playing described in Section 6.9. The author then demonstrated the method of "fingered octaves" in the left hand—i.e., keeping one side of the hand legato while the other side changes position (this technique is illustrated in Figure 6.10). The whole of the opening was then demonstrated and the MOD display used to illustrate the legato techniques involved (see Figure 6.4b).

FIGURE 6.4a Part of the opening of the Moonlight Sonata as played restlessly by H. Notice the gaps* in the melody line which H would usually (and unsatisfactorily) join by using the sustaining pedal.
Next the computerized aid was used to examine timing errors in the 3 against 4 rhythms in bars 5 and 6 of H's playing. H was aware that there were timing errors but was unsure of exactly what was wrong. Slowed-down playback of the passage in question indicated very irregular quavers in the left hand during these rhythms. H then worked at home to improve them accordingly, and also to achieve the legato effects described above. At the next lesson a week later, H's playing of the opening sounded much calmer and both the legato and the 3 against 4 rhythms were nearly correct.

FIGURE 6.4b The much more peaceful playing (demonstrated by the author) of the opening of the Moonlight Sonata in which the melody is played with a fingered legato.
TRILLING

The next student, M, is a computer technician who enjoys listening to rock music. He had received no musical tuition before he agreed to participate in an experimental lesson with the computer. After a brief explanation and demonstration of what a trill is, M was invited to play a trill on the organ keyboard. The MOD display shown at (a) in Figure 6.5 illustrates the jumble that he played. From the repeated asymmetry in the playing of the notes, indicated near the end of the MOD display of his second attempt (shown at (b)), it was deduced by the author that M was holding his hand at the wrong angle to the keyboard. When this was pointed out to M, he tried trilling and changing his hand position until the MOD display of his playing became more regular. By using the feedback provided by the MOD display in this way, M managed - within the space of five minutes - to achieve the acceptable trill shown at (c) in Figure 6.5.

FIGURE 6.5 Three successive attempts at trilling by M, a non-pianist. The feedback provided by the MOD display at (a) and (b) helps M improve his trilling to the acceptable standard indicated at (c).
MOZART’S G MAJOR SONATA

W is in his thirties, having studied the piano in his teens and then taken a ten-year break from lessons. When studying Mozart’s Sonata in G, K283 with the author, it was necessary to explain that the left hand quavers at the opening (known as an "Alberti Bass") are not usually played exactly as written. To illustrate that the first left-hand note of each bar should be held for about double the printed duration, Andre Tchaikovsky’s performance of the passage (described in Section 6-9) was played back to W. By way of comparison, an exactly literal performance of the same passage that had earlier been recorded, edited and filed away by the author (in the manner outlined in Section 6.3) was played back to W. This "literal" performance sounded dry and mechanical next to Andre Tchaikovsky’s playing. The difference between the two methods is clearly illustrated in the MOD display shown in Figure 6.6. W experienced a little difficulty, initially, in sustaining the first, left-hand note in each bar— but by using the MOD display as feedback (as with M and the trill, above) he soon managed it.

![MOD display](image)

**FIGURE 6.6 Teaching interpretation using a stored example.**

At (a) is the MOD notation for what Mozart wrote. (b) shows a concert pianist’s interpretation, in which the first left-hand note in each bar is held on a bit longer.

When W played all of the first movement, on the organ keyboard, the resulting MOD display revealed a note that was being incorrectly held for three times its printed duration! This error had escaped the notice of both W and the author during recording and playback, before seeing the MOD display! Several errors of articulation were also visible e.g. staccato notes that should have been played legato, and vice versa.
At the time of his first session with the computer, W's piano playing was characterized by tense, stabbing, finger movements, which produced a brittle tone and prevented him from playing a true legato ("legato" means smooth, connected - cf. R.S.M., 1958). At the computer, the author explained that legato playing requires, among other things, overlapping of the sound from one note to the next (cf. Milchmeyer, '1698). This overlap was illustrated by means of the MOD display (during playback) of Andre Tchaikovsky's legato playing in the Bach "Aria" (see Figure 6.9). W was then given exercises, designed by the author, to develop the muscular control needed for overlapping (i.e. releasing the key after the next note is sounded). These exercises require that the release of each key occur at a specific part of the rhythm e.g. halfway through the following note. In the space of three weeks, not only did W's finger control improve considerably, but there was also a dramatic improvement in the tone of his playing. This unexpected mellowing of W's tone may have resulted from the uncoupling of the reflex movements of the upper arm from the finger movements. In Kochevitsky's (1967, p.31) opinion, quiet practising of overlapping can give rise to such uncoupling. After six weeks of practising the exercises and applying overlapping techniques to the legato passages in his pieces, W was able to play with a true legato, and could also vary the tone he produced on the piano. In the above way, the MOD display has been used to give an awareness of overlapping, which in turn has enabled W - in practising the muscular control required for overlapping - to greatly improve his tone control.

This section has given brief examples illustrating the effectiveness of the computerized aid for teaching some techniques of piano playing. Aspects taught included the muscular skills required for playing ornaments (J and M) cross rhythms (J) and for tone control (W). MOD display was used to demonstrate to C, musical concepts relating to musical notation. The aspects of interpretation taught included legato (M), articulation (W), and the Alberti Bass (W). MOD display and slowed-down playback were used to reveal faults in J, H and B's playing that would probably have gone unnoticed otherwise. The author has found the aid useful in finding articulation errors in his own playing, and in improving his performance of cross-rhythms. In the sessions with J, W, M and B, described above, care had to be exercised (by the author) in order to prevent too many discouraging details from being revealed by the computerized aid. The analytic power of the MOD display and slowed-down playback is such as to enable inaccuracies to be found in ANY piece played on the computer's organ keyboard (since nobody is perfect). The teacher must decide which parts of the computerized aid's feedback are likely to be most beneficial, for each piano student.
6.7. SUGGESTIONS FOR FUTURE DEVELOPMENT.

6.7.1. IMPROVED FEEDBACK FOR PIANISTS

Having discussed the present capabilities of the computerized aid, ways are now suggested for making it more "natural" to use, and for extending the range of feedback provided. A criticism occasionally made by students (using the aid) is that the computer's organ keyboard is not like a piano to play - the resistance of the keys and the sound produced are those of an electronic organ. Due to the reduced key resistance, some passages (e.g. black note glissandi) are much easier to play on the organ keyboard than on a piano. Thus, if an attempt is made to improve the computerized aid, a high priority must be the replacement of the organ keyboard by a more suitable musical input device - such as the "Bechstein grand piano with built-in sensors" used by Shaffer (1978). (Shaffer has interfaced a Bechstein to a computer in preparation for examining the performances of professional musicians).

6.7.1.1. PEDALLING.

When playing the piano, "each (musical) style requires a different kind and extent of pedal use" (Gat, 1968). The learning of the "kind and extent" appropriate to a particular style is hampered by the difficulty of attending to the feet while concentrating on following the music and playing the correct notes (see limitation (a), in Section 6.4.3). Moreover, Scholes (1950) considers that "careful study of the performance of many pianists will show that they are not pedalling as they intend to do, and believe themselves to be doing." Scholes' view is supported by many examples in the author's own teaching experience. One way of showing students what they are doing would be to attach a contact switch to each pedal and display the output (from the pedal switches) on the screen as illustrated in Figure 6.7. This display could be obtained by inputting the state of the pedal switches to the computer programs in the same manner as the state of the keyboard switches is inputted (see Section 3.2), and making an appropriate modification to the MOD display program. Using the output from the pedal switches proposed above, specially designed computer programs could test for specific pedalling faults e.g. depressing the sostenuto pedal while the sustaining pedal is down. The type of display postulated in Figure 6.7 shows the timing of pedal usage, and would thereby enable teachers to point out timing errors in pedalling to disbelieving students. The provision of such a display might also benefit composers who use MOD notation and who wish to notate pedal usage explicitly (the method of scoring the pedal usage, shown in Figure 6.7, is in accordance with the guidelines set down by Kontarsky, 1970, in his plea for a comprehensible and standardized notation for contemporary piano music).
Suggested extensions to MOD notation include displaying the pedalling, and using thickness to represent the initial loudness of a note. (Ped = sustaining pedal; Sost = sostenuto pedal; U.C. = soft pedal.)

The modifications to a grand piano recommended above (in Section 6.7.1) would enable concert performances to be monitored and analysed. This would allow further research to be made into the effects of "nerves" on public playing (cf. Kochevitsky, 1967, p.52), and the ways of overcoming their adverse effects (cf. Appel, 1976). The resulting computerized system could be used to give concert pianists a new awareness of piano techniques and of their own playing.

6.7.2. A PROPOSED AID FOR SINGERS AND INSTRUMENTALISTS

The computerized aid described in Section 6.3 can - as is now explained - be extended to benefit singers and instrumentalists (the term "instrumentalists" here refers to players of all musical instruments excluding keyboard and percussion instruments). The problems of these musicians are quite different from those of pianists, especially with regard to intonation (i.e. playing in tune) and dynamics (i.e. playing at different levels of loudness). Ways are now suggested in which techniques developed elsewhere can be combined to provide solo players with feedback about pitch, duration, dynamics and intonation. But first, some of the difficulties experienced by musicians are described, and the need for feedback is explained.
A typical person can discriminate hundreds of different pitches by comparative judgement (cf. Frey and Kinsler, 1962). Yet, when Pollack (1952) required subjects to identify tones ranging from 100 to 8000 Hz by using absolute judgement, he found that his best subject could correctly identify only six stimuli ranges. He reported small variability due either to differences between individuals or to gross changes in the range and spacing of tones. These findings are supported by Attneave (1959) who shows that humans are severely limited in their ability to recognize stimuli in a single dimension of either pitch, loudness, saltiness, colour, or position on a line (using only vision). For pitch and loudness, the approximate number of stimuli ranges correctly identified is 6 and 5 respectively. Hartman's (1954) results indicate that extensive practice may increase these figures to 7.

The above findings imply that, in the absence of an external reference, the average musician may drift in pitch or loudness without being aware of it. Such drifting (a common occurrence in the author's violin teaching experience) may be compounded by fluctuations in the musician's subjective sense of loudness. (Riess-Jones, 1976, offers an explanation for fluctuations in loudness estimation). The extensions to the computerized aid that are proposed in the following sections would pinpoint the location of any such drifting and indicate its extent. The augmented feedback thereby provided would help musicians improve the precision of their intonation and dynamics, for the reasons given in Section 6.4.2.2.

An exception to the above is the unusual phenomenon of "absolute pitch" (cf. Jeffress, 1962) in which a person can correctly identify dozens of pitch ranges by using absolute judgement. This little-understood ability seems to be innate and unteachable (cf. Zimmerman, 1975). Even if augmented feedback about intonation is redundant, musicians possessing absolute pitch can still benefit from information about other aspects of their playing (e.g. loudness).

A performer can check intonation by comparing a tape playback of the music with a reference pitch (provided by, for example, a tuning fork or piano). But Siegel and Siegel (1976) have shown that musicians, having identified an out-of-tune note, often cannot tell if it is sharp or flat. In such cases the performer does not know what correction to make. For this reason the tape recorder is considered an inadequate source of feedback about intonation.

Attneave's (1959) and Hartman's (1954) findings reported above imply that when using absolute judgement, most musicians cannot correctly identify all 8 dynamic levels in common use (i.e. fff, ff, f, mf, mp, p, pp, ppp). And the comparative judgement of loudness level is not helped by the crescendos, diminuendos, sforzandos and accents abounding in Romantic music (to make matters worse, the author has even seen "pppppp" printed in an
orchestral violin part). Because tape playback cannot provide absolute information about loudness and there seems to be no aid that provides reference dynamic levels to compare the playback with, the tape recorder is considered an inadequate source of feedback about dynamics.

For the above reasons, singers and instrumentalists may need augmented feedback different from that provided by the tape recorder if they are to perform the exact pitches at the dynamics indicated by the composer.

The next sections briefly outline ways in which the computer might provide the feedback needed by musicians about dynamics and intonation (this need is explained above). Other feedback is also proposed, to help singers and instrumentalists cope with the perceptual limitations described in Section 6.4.3. Ways of coping with human physical limitations are not discussed here — for a review of such limitations affecting woodwind players (including the adverse effects on one's sex life of playing contemporary music) see Lamb (1973).

6.7.2.2. PITCH AND DURATION

When a pitch estimator (such as that described in Section 3.7) is incorporated in the computerized aid, the information supplied to the programs can be used to produce a MOD display of a vocal or instrumental performance (as reported by Tucker, 1977; see also Tucker and Bates, 1977, 1978). This display provides feedback about the durations and cutoffs of notes, which can be used to improve the precision of a musician's legato, staccato and phrasing (for the reasons given in Sections 6.4.2.2. and 6.5.3). Slowed-down playback via the computer's sound generator (described in Section 3.3.3.) magnifies any timing errors in rhythm, and can, therefore, be used to improve the precision of a musician's rhythm (as explained in Section 6.4.2.2).

6.7.2.3. DYNAMICS

In order to obtain computerized feedback about dynamics, sound pressure level information must be inputted to the programs, i.e. a device for measuring sound pressure levels needs to be interfaced to the computer. Clark and Luce (1965) have shown that the dynamic level (e.g. ff, mp) is a function of frequency, sound pressure level, and the type of instrument being played (e.g. clarinet, oboe, flute). Programs can be designed to use these data to calculate the dynamics of a solo performance and display the results in a MOD-type notation such as that shown in Figure 6.7. As well as enabling musicians to become aware of fluctuations in their loudness estimation, such feedback can help players cope with their loudness drift (as explained in Section 6.7.2.1). It would also provide feedback to help students compensate for loudness nonlinearities in their instruments e.g. the "Wolf note" in the cello (cf.Firth and Buchanan, 1973), the "break" in the clarinet and saxophone (cf.Backus, 1968), and the "open strings" of stringed instruments (cf.Fletcher et al, 1965).
6.7.2.4. **INTONATION**

Intonation may be divided into two categories: "relative intonation", in which the performer must play in tune with other players in an ensemble, and "solo intonation" which is measured on an absolute scale. This section deals with the latter type of intonation. The smallest pitch difference detectable by the human ear is about 1/9 semitone (cf. Frey and Kinsler, 1962). Thus, for programs to indicate out-of-tune notes in a solo vocal or instrumental performance, a pitch estimator accurate to at least one-ninth semitone (e.g. that developed by Tucker and Bates, 1977, 1978) must be interfaced to the computer. Special programs would need to be designed to display intonation errors to the performer. The MOD-type notation postulated in Figure 6.8 could be used for such a display. In figure 6.8 out-of-tune notes are represented by rectangles (in place of the usual solid blocks), with adjacent + or - signs indicating sharpness or flatness, respectively. In accordance with the findings of Allvin and Kuhn (1967), namely, that students prefer to set their own criteria of out-of-tuneness, the tolerance with which a note is calculated as being in tune should be adjustable by the musician. Special programs could indicate intonation errors with respect to each of the three main tuning systems - equal temperament, mean-tone tuning, and "just" intonation (cf Jeans, 1945).

**FIGURE 6.8** Intonation faults are clearly seen in this hypothetical form of MOD display. A note that is sharp or flat is indicated respectively by a plus or minus sign next to a hollow rectangle. In-tune notes are represented by the usual solid blocks.

Apart from the taperecorder, which is considered inadequate here (for the reasons given in Section 6.7.2), the only aid that provides feedback about intonation is the stroboscopic tuner (e.g. the Strobotuner - see Conn, 1974) This device uses a rotating pattern on a screen to display the pitch error of a note that is played into a microphone. Clockwise rotation denotes sharpness, anti-clockwise rotation denotes flatness, and the speed of rotation is proportional to the extent of the error. Feedback is almost immediate, but takes time to react to. The
device only works for unwavering pitches (e.g. those without vibrato, portamento or glissando) and is usually set to one tuning system (i.e. the even tempered scale). The main drawback of the Strobotuner is that it requires a different switch setting for each note that is not separated from the preceding note by an integral number of octaves. Thus the playing of an ordinary scale into the Strobotuner requires a switch to be repositioned after every note! This device therefore seems unsuitable for analysing musical performances.

By providing feedback about intonation after a performance, the computerized aid, together with the extensions described above, would allow the performer to concentrate wholly on the music being played. When the playing stops, errors could be detected using the feedback provided (see Figure 6.8) and remedial action taken.

6.7.2.5. FEEDBACK DURING PERFORMANCE

It is perfectly feasible technically to provide the feedback outlined in Sections 6.7.2.2 to 6.7.2.4 while the musician is playing, with a scarcely noticeable delay (e.g. one-tenth second). This would enable the performer to work at notes that are difficult to play softly, or that are hard to get in tune (such feedback would be faster than that provided by the Strobeconn).
6.8. CONCLUSIONS

Sections 6.1 to 6.6 have introduced a new, computerized aid which is easy to operate and which provides feedback about piano playing different to that offered by existing aids. One aim has been to find the benefits that are likely to be attributed to the computerized aid as the result of suitably designed, controlled experiments. After examining piano techniques and considering accepted findings of psychology as they apply to pianists, it is concluded that the computerized aid can have the following beneficial effects upon pianists who use it (the numbers in square brackets indicate the section dealing with that benefit):

a. the playing of rhythms becomes more precise [6.4.2.1];

b. staccato and legato playing improves [6.5.3.1.];

c. less time is required to learn to play cross rhythms [6.6];

d. trills become more even [6.5.3.1];

e. Scales and arpeggios improve due to better passing under the thumb [6.5.1];

f. Alberti basses are played in the correct style [6.9.1];

g. Less time is needed to learn fast passages (since some mistakes are easier to find and hence may be sooner corrected) [6.4.3].

As explained in the sections indicated in the square brackets, the computerized aid is likely to provide the above benefits as follows: by magnifying details of rhythm (benefit (a), above), presenting note cutoffs in an easily perceived form (benefits (b) and (f)), providing an analysis of the performance of cross-rhythms (benefit (c)), presenting a visual analogue of finger and thumb position (benefit (e)) and slowing down fast passages to a speed at which details can be more easily perceived (benefits (d) and (g)). Although Sections 6.6 and 6.9 present evidence that the computerized aid DOES provide the above benefits - and others besides (e.g. it helps pianists to play the correct notes with the proper durations) - verification of these benefits by controlled experiment remains to be carried out.

The next (and final) section describes the reactions of an international concert pianist to the computerized aid. New ideas, as well as those discussed in some preceding sections, emerge from the discussion reported, and the aid's capacity for analysing virtuoso performances is illustrated. The entertaining comments made by the artist - André Tchaikovsky - end the chapter on an optimistic note.
The Aria from the Goldberg Variations by J. S. Bach. At the left is the traditional notation, while on the right is the MOD notation of the performance of the Aria by André Tchaikovsky. Note the perfect trill at (a), the legato bass line, and the impeccable cut-off at (b). Only the first half of the Aria is shown.
6.9. CODA: ANDRÉ TCHAIKOVSKY'S REACTIONS TO THE COMPUTERIZED AID

The informal analysis of André Tchaikovsky's playing reported here together with his comments about the computerized aid, have previously appeared in Lamb (1977a, 1978). They provide an encouraging indication of the likely reactions of pianists to the new aid.

In March, 1977, the international concert pianist, André Tchaikovsky, gave a recital in Christchurch, New Zealand. During a free afternoon he was shown the interactive musicianship aids system outlined in Section 3.2. An account is now given of André Tchaikovsky's reactions to the computerized aid described in Section 6.3. A number of the uses of the computerized aid for analysing piano performance, as outlined in preceding sections, are illustrated. Details revealed by MOD and slowed-down playback indicate the potential of the computerized aid with regard to teaching and practising the piano. For example, Figure 6.9 illustrates the MOD notation for the first piece that André Tchaikovsky played to the computer (-Bach's "Aria" from the Goldberg Variations). The conventional notation is displayed alongside for comparison. Notice how easy it is to recognise the perfect trill at (a) and the impeccable cutoffs at (b). Also visible is a legatissimo bass line.

After the above initial trial, André Tchaikovsky played the opening bars of the Moonlight Sonata, after which the following impromptu analysis of his performance took place.

6.9.1. AN INFORMAL ANALYSIS

Abbreviations: A = André Tchaikovsky M = Martin Lamb
SPB = playback at 1/3 speed (Pitch is unchanged).

All the musical terms used are clearly explained in R.S.M. (1958). The following is a condensed account of what happened.

MOONLIGHT SONATA.

M. I'll make the computer slow that down so we can hear how you play the three against four rhythm. <at (b) in Figure 6.10>

A. Oh, but I don't play it exactly three against four -- I do it Tovey's way. He says that to play three against four makes a "click" in the rhythm.

M. Do you play it evenly then? <See Craxton and Tovey (1931)>

A. Yes -- the semiquaver becomes half the length of the triplet quaver. <The music is played back at 1/3 speed by the computer programs. A large amount of rubato slowing down is apparent during "three against four" parts.>

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**FIGURE 6.10** The opening bars of Beethoven's "Moonlight Sonata". The legato octaves in the left hand are seen to "phrase off" at (a); while at (b) there is a deliberate departure from what Beethoven wrote (see text). (The music on the right has been transposed up an octave, using computer programs, for ease of viewing.)
A. Goodness me! I must have done that <rubato> because I was playing it all too fast.

M. It's because it's slowed down so much you can hear all the rhythm details terribly exactly. Those would be rather nice nuances, at the original speed.

M. And what about the last movement? <André plays the opening bars of the Presto.>

M. Would you like to hear it played back? <SPB>

A. Don't be so cruel! Did I really play all those wrong notes? <The organ keyboard shown in Figure 3.1 is more sensitive than a concert grand piano. As a result, the bumping of keys, indicated by "blips" in Figure 6.11, would probably not be audible on a piano. About a dozen such blips have been erased from Figures 6.9 to 6.15.>

FIGURE 6.11 The beginning of the last movement from Beethoven's "Moonlight" Sonata.
KREISLERIANA

M. What about playing something fast and tricky?

A. Alright -- I'll play you something that I know won't be quite right. <Plays> -- Oh, there's no top D! <The keyboard is only 5 octaves and ends at C.>

M. Would you like to hear that back?

A. Not really. <SPB> -- Oh, my goodness!

M. Is that the right rhythm?

A. There are meant to be even triplets all the way through -- It's OK at the beginning but later on they get all irregular. Let me try it again.

M. That's better, and there are fewer blips.

A. Let's try another piece.

TRIPLE TRILLS

M. Would you mind very much playing the triple trills after the last movement cadenza of Beethoven's Fourth Piano Concerto?

A. All right -- but they're brutes of things to play. <Plays> <SPB>

A. Help! What a hotch potch! <Looks at screen> They're very blurred aren't they? <See Figure 6.12 (a). Ideally, the trill should appear as alternating block chords. André plays this trill by taking the F sharp, C, A in the left hand and the G, D, B with the right hand.>

A. May I try it again? I'll try and get it clearer. <Plays. SPB> That's a bit better. Let's try something else.

MOZART'S SONATA IN G

<He plays the opening of the first movement. From the resultant notation on the screen it can be seen that the first note of each group in the Alberti Bass is held for about twice the printed duration. (See Figure 6.13)>

A. Oh look! I held on those notes in the left hand. That might have been because I didn't have a pedal to use. <SPB>

M. That's a beautifully clear run.
FIGURE 6.12 The difficult triple trill from Beethoven's Fourth Piano Concerto. At (a) is the MOD notation of André Tchaikovsky's first version. (b) shows part of the much improved second attempt made after a careful scrutiny of the irregularities revealed by (a).

Allegro. ($J = 132.$)

FIGURE 6.13 The beginning of Mozart's Sonata in G K.283. (Barlines have been added using computer programs.) The left hand quavers are an example of an "Alberti Bass".
FIGURE 6.14 The celebrated Waltz by A. Diabelli. An illusion is revealed. The acciaccaturas (marked a) are deliberately sustained to produce the effect of the rhythm indicated by the composer. The pedantically "correct" procedure (marked b) would not normally have any overlap between the two notes involved.

DIABELLI WALTZ

M. That grace note -- are you aware that you held the first two notes together? Was that intentional, to get a "bite" or clash to make it exciting? <See Figure 6.14.>

A. No -- I didn't realize I was doing that at all -- it's not intentional. <He plays it carefully, without any overlap.> -- You see! That is how it is written. <He tries it both ways.>

M. Would you play it any differently as a result of seeing this on the screen?

A. No, I don't think I would. You see, if I play it exactly, then at the speed that the piece goes it sounds rather like a triplet, which is wrong. You see? <He plays.> But if I put the first two notes down almost together, then it gives the illusion of being the right rhythm, which is better than the "exact" way.
M. If you were trying to explain all this to a pupil, would you find our system helpful? -- Being able to see the way to play it?

A. The trouble is -- I don't know exactly how I play so I can't explain to pupils what it is that I do.

M. But by playing to the computer you can find out what you actually do play.

A. That's right -- but it's a new way of doing things.

ONDINE <Plays. SPB.>

A. I am surprised at how well I played that. Normally it takes a lot of preliminary practice. You know -- this is the type of piece where, if it's correct nobody notices, but any note or rhythm that's wrong is immediately obvious. It's like a nose -- a beautiful nose is never noticed, but misshapen or unusual ones always stand out.

M. How would you practise this piece -- slowly?

A. Yes -- for hours and hours.

M. Does not having a pedal bother you?

A. Not really. Normally I would put the pedal down before the very first note -- to create a sort of shimmering effect. With the Kreisleriana, of course, there is next to no pedal anyway because of the rapidly changing harmonies.

M. Is the rhythm correct here?

A. It should be 123, 123, 12 repeated over and over until the fifth bar. <See Figure 6.15.>

M. <Counting them out on the screen.> Yes -- they're all OK.

M. Would you find this useful for teaching?

A. Definitely! You know it's terribly frustrating when a complacent pupil can't hear the mistakes he's making.

M. What do you do to try and show him that he's wrong?

A. Bring out the tape recorder, mostly. The trouble is -- if he can't hear the mistakes while he's playing, often he also can't hear them when it's being played back. While -- here on the screen, the music is frozen in front of your eyes. You can spend ten minutes just looking at that <points to screen> and going over it.
M. How useful do you think this would be for teaching?

A. Fantastically helpful. It is the ultimate deterrent for lazy pupils. The slowed down playback is very revealing -- that is the best feature. But the notation on the screen would, maybe, take three lessons to get completely familiar with.

It must be emphasised that André Tchaikovsky came to see the computer without any prior rehearsal. All the music was played from memory, without the use of pedals, and on a keyboard that is more sensitive than that of a normal piano. Nevertheless, some of the exciting possibilities of the computerized musicianship teaching aid emerged during the above session. It is fascinating to see how a great pianist plays. For all of us working in the computer/music field, it is a challenge to realize that the computer can help in the teaching and analysis of keyboard technique, even at the virtuoso level.
The fluttering right hand interwoven with the slow left hand melody of Ravel's "Ondine". The accuracy of the complex rhythms can be assessed either visually or by slow playback by the computer programs.
7. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1. CONCLUSIONS

The main contribution of this thesis is that it shows that computer programs can be written in a way which enables music instructors to use the computer to improve the quality of their teaching. The results presented in Chapters 3, 4, and 6 indicate how this is done in the subjects of aural training, harmony instruction and piano teaching, respectively. The potential improvement in the quality of instruction received by the student and the ease of operation by the instructor make each of the computerized teaching aids reported in this thesis more advanced than the corresponding aids reviewed in Chapter 2, as is explained below. Moreover, as is shown in Sections 3.3, 4.4 and 6.3, little specialized training is required by the instructor in order to use these teaching aids.

The computerized system for aural training described in Chapter 3 adapts to individual students' weaknesses (as described in Section 3.3 and demonstrated in Section 3.5.1). The programs function in a way which surpasses any person's capacity for patience and taking pains. Section 3.4 explains how, by providing immediate precise feedback and individualized pacing, the computerized aural training system (described in Section 3.3) overcomes the two problems, associated with class music teaching, identified by Ihrke (1963). Kuhn's (1974) training system (which is similar to that of Hofstetter, 1975) provides immediate feedback and individualized pacing, but does not interactively adapt to individual students' specific problems. Furthermore, Kuhn's system requires the alphanumeric coding of musical examples in order to specify the computer-student interaction. This tedium is avoided by inputting the musical examples directly (as described in Section 3.3.3) by playing them on an organ keyboard interfaced to the programs.

Chapter 4 demonstrates how the computer can aid the teaching of advanced music theory, in particular the creative subject of four-part harmonization. Previously reported computerized systems for teaching music theory are limited to elementary material of a non-creative nature, as explained in Section 2.3.7. The programs reported in Sections 4.2 and 4.3 assess student harmonizations for standard harmony "errors" more meticulously than is humanly possible, as is explained and demonstrated in Section 4.5.1. Sections 4.4 and 4.5.2 show how each erring student receives individual attention by the programs, in the form of another harmonization of the same melody based on the student's work but without containing any of the errors detected there. This alternative harmonization provides constructive criticism which is also creative - a type of service not offered by any of the computer systems reviewed in Chapter 2. The use of an organ keyboard for inputting student harmonizations directly to the programs is a more convenient method of entering harmony than is the case with previously reported systems for teaching music.
theory, which use typewriters or touch-sensitive panels for student responses.

The results presented in Chapter 6 demonstrate how the computer system developed by Tucker et al (1977) is used for piano teaching. Section 6.4 explains how this system enables subtle faults to be revealed in a student's playing. Due to the limits of human auditory perception (noted in Section 6.4.3), such faults may occur too quickly for the instructor to identify exactly, even with the help of existing aids (as is explained in Section 6.2). Section 6.4.4 explains how the MOD display and slowed-down playback of a performance can be used to overcome human perceptual limitations associated with fast playing, articulation, and the performing of complex rhythms. Sections 6.3 and 6.6 show how the computer is used to assess the performance of cross-rhythms - a performance skill that is difficult to teach using existing aids (for the reasons given in Section 6.3). Results presented in Sections 6.9.1 and 6.6 demonstrate how the computerized aid is used for the analysis and teaching of aspects of style and interpretation. Much of the analysis described could not have been carried out as conveniently with existing aids, for the reasons given in Sections 6.5.1 and 6.5.3.

Although the computerized systems to aid aural training, harmony assessment and pianoforte teaching are the main concerns of this thesis, a subsidiary topic has arisen during the development of the harmony assessment system, namely the system for interactive harmonization described in Chapter 5. The results presented in Section 5.4 show that programs can be made to harmonize in a particular style with high-level interactive guidance from a musician. The use of interaction, passing notes, and programmed "musical intuition" (i.e. the derived rules described in Section 5.2.2) all represent improvements on the harmonizing programs reported to date.

In the ways described above, aural instructors, harmony tutors and pianoforte teachers can improve the quality of their teaching. The computer is used to provide more precise and immediate feedback than instructors can provide. It is also used to adapt aural training to the individual student's capabilities and needs. By revealing details of performance that are virtually impossible to detect otherwise, the computer can help pianists improve the precision of their playing. The effectiveness of the above computerized aids is illustrated by the results presented in Sections 3.5, 4.5, and 6.6.

By assisting with the acquisition of the skills that musicians need in order to be creative, the computer is seen to be an effective aid in the teaching of musicianship.
7.2. SUGGESTIONS FOR FUTURE RESEARCH

Although the computerized systems reported in Chapters 3, 4, and 6 have been shown to be effective aids to instruction, their scope can probably be extended by implementing the suggestions made in Sections 3.6, 4.6, and 6.7. In particular, the aural training system can, it is explained in Chapter 6, be extended to accept sung and tapped responses from the student. Ways of overcoming problems associated with assessing such responses are suggested.

Section 4.6 outlines the benefits and convenience of replacing the input and output devices used in the harmony assessment system, with a mark-sense reader and an on-line Xerox printer. It is explained that the musical sophistication of the assessment programs can probably be increased by the use of techniques developed by Lovelock (1947) and Winograd (1968). This increase in sophistication should ideally be matched by a similar improvement in the harmonizing programs. Ways for achieving this - by incorporating modulations and passing notes into the programs' harmonizations - are outlined in Section 5.6, together with examples demonstrating these methods' feasibility.

In Section 6.7.1 it is indicated how a piano could replace the organ input to the computer. The improved feedback available from such a piano teaching aid would be most beneficial. Section 6.7.2 explains how the aid can be extended to accept input from other instruments and voice, by means of a pitch estimator interfaced to the programs. This extension might be used to help singers and instrumentalists overcome perceptual limitations associated with intonation and dynamics, as is explained in Section 6.7.2.1.

Finally, the author hopes that these aids will one day be installed in a musical institution, somewhere. It is only by musicians using computerized systems such as those reported here that the computer's full potential as a musicianship teaching aid will eventually be realized.
The first step carried out by the programs is to transpose each note of the chord up or down the necessary number of octaves to take it to the octave above (and including) Middle C. The resulting group of pitches is called a "concentrate" here (it is analogous to the "close position" of the chord). This concentrate is then compared with each of the chords displayed in Figure A1.1. If it does not match any of these, the concentrate is transposed down a semitone and again compared with each of the chords of Figure A1.1. If it still does not match, it is transposed down another semitone and compared again. And so on. Whenever one of the notes of the transposed concentrate is Middle C, this note becomes the B above Middle C at the next transposition step. The whole procedure stops when a match is found. It also stops if the concentrate goes through 12 transposition steps (when it reaches its original state, since there are 12 semitones in an octave) without being matched.

FIGURE A1.1 The programs identify all the above chords in any inversion or key. During the matching process, the students' chords are converted into "close harmony" in root position, and then transposed for comparison with the above chords. (* indicates an incomplete chord i.e. the fifth is missing.)
If the (transposed) concentrate is matched to one of the chords of Figure Al.1, the original chord's type is the same as that of the matched chord (see Figure Al.1). The root pitch is then taken to be the same number of semitones above C as there were transposition steps when matching the concentrate. The inversion is found by transposing the bass note, first down the same number of semitones as there were transition steps, and then up the number of octaves needed to take it to the octave above middle C. There, it is compared with the notes of the matched chord. If the transposed bass is the same as the bottom of the matched chord note, the original chord is in root position. If the transposed bass is the same as the first note above the bottom note, the original chord is a first inversion. And so on.

If the (transposed) concentrate is not matched to any of the chords of Figure Al.1, the root pitch of the chord is estimated in the following manner.

**Al.2. ESTIMATION OF ROOT PITCH**

Most musicians, when estimating the root pitch of a group of simultaneously sounding notes, would rely fairly heavily on the note names. Unfortunately, the letter names of the notes are not directly available from the organ input. C♯ and Db are inputted in an identical manner, for example. This ambiguity can sometimes be resolved from the context of the key (which the programs do not know at this stage) or from the context of the note names of the rest of the chord (which are not directly available, either). Rather than resolve these ambiguities, I have devised a convenient algorithm for estimating the root pitch that does not use note names. This algorithm is now described.

First, the notes of the chord are transposed to form a concentrate as described in the preceding section. Then, the concentrate is given a "tally", calculated by adding together the "weights" of its component notes (these weights are given in Table Al.1).
### ROOT PITCH ESTIMATION

<table>
<thead>
<tr>
<th>PITCH</th>
<th>&quot;WEIGHT&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>7</td>
</tr>
<tr>
<td>A♯ or B flat</td>
<td>8</td>
</tr>
<tr>
<td>A</td>
<td>2</td>
</tr>
<tr>
<td>G♯ or A flat</td>
<td>6</td>
</tr>
<tr>
<td>G</td>
<td>9</td>
</tr>
<tr>
<td>F♯ or G flat</td>
<td>7</td>
</tr>
<tr>
<td>F</td>
<td>5</td>
</tr>
<tr>
<td>E</td>
<td>10</td>
</tr>
<tr>
<td>D♯ or E flat</td>
<td>11</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
</tr>
<tr>
<td>C♯ or D flat</td>
<td>1</td>
</tr>
<tr>
<td>C</td>
<td>12</td>
</tr>
</tbody>
</table>

**TABLE A1.1** Each pitch of a chord has its weight tallied to give a total for that chord. This total is calculated for each of the 12 transpositions of the chord. The transposition with the highest tally indicates the root pitch, as is explained in the text.

The concentrate then undergoes a transposition step as described in the preceding section. A new tally is calculated by adding together the weights of the new, transposed notes. Twelve tallies are obtained in this way when the concentrate has undergone 11 transposition steps. The root pitch is then estimated as being the same number of semitones above C as there are transposition steps associated with the largest tally. For example a chord containing only A's and D's would have its root pitch estimated as D. This is because D is 2 semitones above C, and the highest tally, 21, for the (transposed) D A concentrate occurs at the second transposition step (when D A is transposed down 2 semitones to C G).

The results of the above algorithm usually agree with musicians' estimates of root pitch. This is the case with the 3 marked discords in Figure 4.3, for example.

This algorithm works because it, like Gabura's (1965) method, is based on the observation that, in tonal harmony, most chords are derived from superimposed thirds. The weights shown in Table A1.1 are arranged in a way that reflects a decreasing order with thirds ascending above the note C.

At this stage of the computerized analysis, the following information has been deduced for most chords: (1) a root pitch (2) a chord type and (3) an inversion. For each of the remaining chords, the root pitch has been estimated. The next step - finding the key - is described in Chapter 5.
APPENDIX 2: AURAL TRAINING BY COMPUTER

A2.1. GUIDEBOOK FOR STUDENTS

Welcome to aural training with JEMIMA the musical computer! You'll find that working with JEMIMA is just like practising aural with a friend, except that JEMIMA is very patient and doesn't mind if you make mistakes. She's quite happy to play the same aural test over and over again, on demand (while you decide what the answer is). And like a true friend JEMIMA helps you with your problems, by pointing out your trouble spots so that you can work on them at home, afterwards.

FIGURE 1

JEMIMA

FIGURE 1 The layout of JEMIMA. (The "Enter" button is shown at "a".)

SOME DOs AND DON'Ts

DO make yourself quite comfy before starting the lesson.

DON'T touch anything other than the console typewriter, electronic organ, and the shelf shown in Figure 1. Everything else (including flashing lights) is NOT to be prodded, tickled, or disturbed. We have to insist on this - the computer facilities cost many thousands of dollars, and we want you (and others) to
be able to continue enjoying the benefits of lessons with JEMIMA.

DO get up, have a stretch, and wander around if you get tired or bored during the lesson - JEMIMA won't mind at all.

DO make a note of your scores with JEMIMA and keep a record of everything she asks you to work at.

DO tell your aural supervisor i.e. Mr Lees (or ring me at 556-858) if you experience any hassles with JEMIMA. Good luck!!

WELCOME TO A FRIENDLY AURAL TRAINING SESSION!
PLEASE TYPE YOUR NAME & PRESS THE "ENTER" BUTTON. ROBIN MCNEILL
GET IN BEHIND! NOW, PLEASE TYPE THE DATE: 7/6/78
ER GIDDAY! WHICH AURAL TEST WOULD YOU LIKE, TREV? 32
TEST 32 DA
2 CHORD CADENCE RECOGNITION. LISTEN TO THE BASS NOTES.

PLEASE PRESS "RETURN" WHEN YOU'RE READY.

FIGURE 2 After making your reply (underlined) to JEMIMA's question, don't forget to press the "ENTER" Button (at *).

HI THERE!!

AFTER HEARING EACH TEST, TYPE THE NUMBER YOU THINK DESCRIBES IT BEST. THEN PUSH THE BUTTON MARKED "RETURN".
(IF YOU'D LIKE TO HEAR ANY TEST AGAIN, JUST PUSH THE "RETURN" BUTTON.)

GOOD LUCK!!!

1 PLAGAL (AMEN)
2 PERFECT ("THE END")
3 INTERRUPTED
4 IMPERFECT CADENCE

FIGURE 3 An explanation of what to do for the tests appears on the screen.
YOUR LESSON: WHAT TO DO

Please wait till JEMIMA has asked you something before you reply (she will ignore you, otherwise). And each time you finish replying to JEMIMA you must press the button labelled "ENTER" on the console typewriter.

The aural training session begins when you type your name (and press the "ENTER" button). When JEMIMA asks which aural tests you'd like (see Figure 2) just type the number of the aural training module you wish to work at (your aural supervisor will advise you which modules to study).

Next, an explanation of what to do appears on the display screen (see Figure 3). You should find the answer sheet that matches what you see on the screen. Read it carefully, noting the number next to each answer. Then press the button labelled "RETURN", and the music commences!!

When you'd like a change from the present aural tests, just type "END". If, after noting your trouble spots, you'd like to finish the training session, type "END" again. The whole procedure is summarized in Figure 4. You're sure to find it a piece of cake!

1 TYPE NAME and DATE
2 TYPE Aural-training MODULE NUMBER. FIND ANSWER SHEET
3 LISTEN TO AURAL TEST
   DO YOU KNOW THE ANSWER?
   yes   guess   no
   Type the answer's number
   Press "RETURN" button
4 TYPE 'END' TO FINISH MODULE
5 WRITE DOWN SCORE & EXTRA WORK SET
   Is time up?
   no   yes
6 TYPE 'END' TO FINISH

FIGURE 4 A summary of what to do.
SETTING UP THE SYSTEM

1. Move electronic-organ trolley from room R9 to the Hybrid Computer Laboratory.

2. From the metal shelves at the East wall of the Lab. get Logic Panel 8. Fit it to the EAI 580 computer - roll down lever, insert panel, and roll up lever.

3. At the EAI 580 control panel, push in the following buttons:
   a) "Power on" <lights come on>
   b) "DIG"
   c) "10"
   d) Logic mode "RUN" i.e. chalky button <lights flash>.

4. At the EAI 640 computer, press "POWER ON" button. If it won’t stay in, go to rear of second (R.H.) cabinet and check that the cutout switch is ON (and try again).

5. Plug in the electronic organ (to a power socket), and play a few notes. If there is no sound, check that
   a) co-axial cable input at back is plugged in
   b) volume gain is set 0 next to (0)
   c) screw-on volume (dymo) is set at 10 o’clock
   d) red button at back of volume gain box is pushed in

6. Carefully attach plugs 054, 055, 056, 154, 155 and 156 to their respective sockets on the red and green BDI panel <the organ grunts low F>.

7. Get tape T97 from the steel cabinet, 4th door down. At the computer’s magnetic tape unit,
   a) Turn on "Write Lock"
   b) Check "1" is facing on the rotating disc; and check that the "Remote" switch is off (i.e. the rocker switch is at the centre position).
   c) Affix T97 firmly to the LH spool-holder
   d) Load tape by winding plenty of tape onto the RH spool
   e) Push "Remote" in. If tape does not become tensile, press "Mag Tape" button at the EAI 640 control panel.
8. PRERUN: At the EAI 640 control panel,
   a) Check "RUN" button is out
   b) Press "RESET I/O"
   c) Press "RESET CMPTR" <many lights go out>
   d) No sense switches on
   e) All toggle switches up
   f) Press "P" in (it may already be so)
   g) Press "ENTER" <lights 2 to 15 come on>
   h) Press "Execute RUN" <typing happens>
   (The computer may need to warm up, so if nothing
   happens, do this prerun again)

9. STARTUP: At the console typewriter,
   a) Type "#X,0" (note the difference between shift and
      capitals), then press "ENTER". If yellow light does
      not come on, press "Display" button on EAI 640
      control panel.
   b) Below the screen, press "Load" <computer types
      "LOAD - Y OR N?"> Type "Y" and press "ENTER". <"HI
      THERE" from computer>
   c) Computer asks "TASK?". Type "MAPIT" <screen fills
      with words>. If nothing happens on the screen, press
      the "ERASE" button several times.
   d) Press space bar, (and check that the toggle
      switches below the screen are off, off, on, off).

10. SYSTEM SELECT:
   a) Press sense switches A and B in <they light up>
   b) Below screen, press "Keyboard File" button.
      <computer asks File name>
   c) Type "HARMOl" <computer asks for paper to be
      advanced to a new page>
   (If anything goes wrong, go back to Step 8).
APPENDIX 3: A CONTEXT-BASED INVESTIGATION OF BACH CHORALES

In order to improve the computer harmonizations, i.e. make them more Bach-like, ways were sought of having them imitate Bach's harmonizing traits. The following experiment uses a novel method to attempt to identify such traits. The results suggest that Bach is more subtle than we had hoped.

A PUSS (see Andreae, 1977, Chapter 2) is a computer program which receives as input, "events", each of which is associated with a "context". In the experiment described here, an event is defined as a single musical contextual feature e.g. a root pitch; and a context is defined as a sequence of musical contextual features e.g. melody notes. Whenever a PUSS receives a context that has been inputted to it on an earlier occasion, the event that was associated with that earlier occurrence is recalled. This recalled event, called a "prediction", is termed "successful" if it then occurs. Throughout this appendix the terms "context", "event" and "prediction" have the special meanings just explained. A method for obtaining events and contexts from Bach chorales is now described.

A3.1. PREPARING CHORALES FOR ANALYSIS.

When preparing a chorale for inputting to PUSSes, a number of simplifications are made. Firstly, most of the unessential notes and unessential chords are omitted. Those that are retained are done so, to obtain a one-to-one correspondence between melody notes and root pitches. The purpose of this omission is so that passages which are essentially the same should be treated as though they are the same, by the programs. A grosser simplification is the disregard of rhythm, which is done both to avoid complications (with regard to the computerized analysis) and because the harmonizing programs described in Chapter 5 manage without rhythmic information. The resultant representation, exemplified in Figure A3.1, is referred to as the "skeleton" form of a chorale. Finally, it is assumed that a Chorale is unchanged by transposition into another key.

In the skeleton forms of Bach Chorales 1 and 6 displayed in Figure A3.1, there are four groups of melody notes marked with brackets. All four groups comprise the same five-note melody fragment (transposed into different keys). At each bracketed occurrence Bach uses the same root pitches for the last three notes, relative to the melody! This seems to be an example of a stereotyped approach to the perfect cadence, of the type observed by Lovelock (1970) (see observation 2 in Section 5.5.3). The way in which this characteristic is detected by the use of Andreae's (1977) PUSSes is now described.
FIGURE A3.1 At (a), the "skeleton form" of Chorale 6 is shown below Bach’s harmonization. (b) shows Chorale 1 with it’s skeleton form, in which all unessential notes and chords are omitted and rhythmic details ignored.
In the experiment, four PUGSes are employed as follows: PUGS-1 receives root pitches as "events" (the terminology is explained in the preceding section). Each root pitch "event" is associated with a "context" comprising the five root pitches preceding it in the skeleton form of the chorale. The purpose of this PUGS is to determine the existence of traits similar to the "usual" root pitch progressions noted by Piston (1949).

PUGS-3 also receives a root pitch as each event, but the "context" in this case is the melody fragment beginning 3 notes before that root pitch and ending the note afterwards—a total of five melody notes altogether. The object of this PUGS is to find the extent to which similar melody fragments are harmonized with the same root pitches.

In some of Bach's chorales there occurs a type of passage called a "sequence". This is a more or less exact repetition of a melody (often with its harmony) at another level, higher or lower (cf. Scholes, 1950, p. 859). In order to find the extent to which Bach repeats root pitch progressions at another level, PUGS-2 is inputted with root pitch jumps as events (a "root pitch jump" here refers to the interval between two successive root pitches). Each event (i.e. root pitch jump) is associated with a context comprising the four root pitch jumps preceding it. In this way, transposed root pitch progressions of more than 4 notes are treated as the same, by PUGS-2.

\[ M_i \] is the i\textsuperscript{th} melody note;
\[ RP_i \] is the root pitch of the notes sounding at the time of \( M_i \);
\[ MJ_i \] is the melodic leap from \( M_i \) to \( M_{i+1} \) measured in semitones;
\[ RJ_i \] is the corresponding jump in root pitch expressed in semitones modulo 12.

The ranges of values which each of these quantities can take are given by

\[ <M_i> =: 10|11|12 \ldots |42 = \text{pitch measured in semitones above the lowest keynote of the Chorale in the bass range.} \]

\[ <RP_i> =: 0|1|2 \ldots |11 = \text{number of semitones above the keynote of the Chorale.} \]

\[ <MJ_i> =: -22|\ldots|0|1|\ldots|25 = (M_{i+1} - M_i) \]

\[ <RJ_i> =: 0|1|2 \ldots |11 = (RP_{i+1} - RP_i) \text{ modulo 12.} \]

\begin{table}[h]
\centering
\begin{tabular}{|c|}
\hline
\textbf{TABLE A3.1} & The features of Bach Chorales that are inputted to the PUGSes. The way in which they are inputted is indicated in Figure A3.1 and Table A3.2.
\hline
\end{tabular}
\end{table}

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Finally, PUSS-4 also receives root pitch jumps as events, but in this case the context comprises the three melody jumps preceding the root pitch jump (event), together with the melody jumps during and immediately following it—a total of five melody jumps altogether. This PUSS is used to find the existence of traits such as stereotyped approaches to the perfect cadence, when these cadences occur in different keys (as is the case with the bracketed notes in Figure A3.1). The usage of the four PUSSes just described is summarized in Tables A3.1 and A3.2, and represented schematically in Figure A3.2.

FIGURE A3.2 Contexts and "Predictions" of the PUSSes.
The schematic representation of part of a chorale skeleton is shown at (a). The inputs to the PUSSes are shown at (b).

- note = melody note
- root pitch = root pitch
- =melodic leap
- =root pitch leap
- indicates the associated event of a window (or context)
Since PUSSes 1 and 3 deal with root pitches and melody notes, they treat as different, repetitions of root progressions and melodies that are transposed. However, repetitions of this nature (as occur commonly in a musical sequence) are not differentiated by either PUSS-2 or PUSS-4 because the leaps of a transposed melody (or root pitch progression) are identical with those of the original. Henceforth, the term "Root Pitch PUSSes" refers to PUSS-1 and PUSS-2, while "Melody PUSSes" refers to PUSS-3 and PUSS-4.

A3.2. THE EXPERIMENTAL PROCEDURE

The six chorale "skeletons" (obtained as explained in the preceding section) are inputted to the four PUSSes (described above) as follows. The keynote of each chorale is entered on the console typewriter. Then the first melody note (from Chorale 1's skeleton) and its accompanying root pitch are inputted, followed by the subsequent melody note - root pitch pairs (encoded on punched paper tape). Using this data, the author's program calculates the events and contexts as defined in Tables A3.1 and A3.2, and inputs them to the four PUSSes.

Chorales (i.e. their skeleton forms) are inputted in numerical order (i.e. Chorale 1 is inputted first, followed by Chorale 2, and so on). In between chorales, five dummy melody note - root pitch pairs are inputted, so as to differentiate the beginning of each chorale and to prevent spurious contexts being generated between the ending of one chorale and the beginning of the next.

<table>
<thead>
<tr>
<th>Context</th>
<th>Prediction</th>
<th>Window Length</th>
</tr>
</thead>
<tbody>
<tr>
<td>Root pitch</td>
<td>RP_{j-3}, RP_{j-2}, RP_{j-1}, RP_j</td>
<td>RP_{j+1}</td>
</tr>
<tr>
<td>Root pitch</td>
<td>RJ_{j-4}, RJ_{j-3}, RJ_{j-2}, RJ_{j-1}, RJ_j</td>
<td>RJ_j</td>
</tr>
<tr>
<td>Melody</td>
<td>M_{j-3}, M_{j-2}, M_{j-1}, M_j, M_{j+1}</td>
<td>RP_{j+1}</td>
</tr>
<tr>
<td>Melodic</td>
<td>M_{j-4}, M_{j-3}, ... M_{j}</td>
<td>RJ_j</td>
</tr>
</tbody>
</table>

TABLE A3.2 The "contexts" i.e. sequences of musical features, that are inputted to the PUSSes. These contexts are represented pictorially in Figure A3.2.
A3.3. EXPERIMENTAL RESULTS

When the procedure outlined in the preceding section is carried out, the six Chorales receive quite varied treatment from the four PUSSes, as is indicated by Table 6.3. Whereas Chorale 1 features four predictions from the root pitch PUSSes and fifteen from the melody PUSSes, this trend is reversed in Chorale 3, for which the corresponding numbers of predictions are respectively twenty-one and three! Despite this variety, some overall trends in prediction can be observed. At the beginning of a chorale, root pitch PUSSes usually predict, mostly with success. Then, after a period with next to no predictions, all PUSSes begin predicting again, with melody PUSSes usually being the more successful. This makes some sense musically: A chorale traditionally begins with the tonic or dominant chord in order to establish the tonality in a fairly stereotyped way (using chord progressions). The melody is usually quite different between chorales, so one would not expect melody PUSSes to predict much at the start of a chorale. However, chord progressions and melody are often developed to give an overall cohesion throughout the chorale. Whether the PUSSes’ predictions reflect this last state of affairs or not, cannot be decided from the sequential inputting of Chorales described here, or from such a small sample. It is an interesting possibility.

<table>
<thead>
<tr>
<th>Chorale number:</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>1 to 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>PUSS-1 (root pitches)</td>
<td>successful:</td>
<td>0</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>unsuccessful:</td>
<td>2</td>
<td>1</td>
<td>5</td>
<td>4</td>
<td>10</td>
<td>4</td>
</tr>
<tr>
<td>PUSS-2 (root pitch leaps)</td>
<td>successful:</td>
<td>0</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>11</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>unsuccessful:</td>
<td>2</td>
<td>3</td>
<td>10</td>
<td>6</td>
<td>22</td>
<td>8</td>
</tr>
<tr>
<td>PUSS-3 (melody notes)</td>
<td>successful:</td>
<td>9</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>unsuccessful:</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>PUSS-4 (melodic leaps)</td>
<td>successful:</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>unsuccessful:</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>6</td>
<td>3</td>
</tr>
</tbody>
</table>

| Melody PUSSes | successful: | 13 | 4 | 2 | 1 | 9 | 5 | 34 |
| (PUSS-3 + PUSS-4) | unsuccessful: | 2 | 2 | 1 | 0 | 8 | 5 | 18 |
| Root Pitch PUSSes | successful: | 0 | 2 | 6 | 5 | 16 | 4 | 33 |
| (PUSS-1 + PUSS-2) | unsuccessful: | 4 | 4 | 15 | 10 | 32 | 12 | 77 |

TABLE A3.3 PUSS predictions made during the input of Bach Chorales 1 to 6. Successful predictions are those that match Bach’s choice of root pitch.

When more than one PUSS is predicting, it is arranged that any predictions made by PUSS-3 are outputted before those of PUSSes -4, -1 and -2 in that order. Preparatory experiments (cf. Lamb, 1977a) indicate that with this order of precedence, the first prediction outputted is more likely to be successful i.e. match
Bach's choice of root pitch. Table A3.3 gives the success rates of individual PUSSes only. PUSS-3 is clearly the most successful. The Table does not include results from using "multiple contexts" in which the predictions from a combination of different PUSSes are ordered according to the above algorithm. In the experiment, there are 90 occasions altogether on which one or more of the PUSSes make a prediction. On approximately half of these occasions (43) the first prediction outputted matches Bach's choice of root pitch.

The high rate of success (80%) of PUSS-3 predictions indicated in Table A3.3 shows that in these six Chorales Bach harmonizes identical 5-note skeletal melody fragments with the same penultimate root pitch 80% of the time (when the Chorales are transposed to the same key). This is interesting because there seems to be no harmony rule that relates melody directly with root pitch. However, this finding is in agreement with observations (i), (iii), (iv) and (v) of Section 5.6. More surprising is the comparatively poor performance of the root pitch PUSSes: a 30% success rate only. Although these PUSSes do not receive details of pulse or chord inversion, nor does the harmonizing program which functions adequately by choosing root pitches from the preceding two and checking for compatibility with the melody note. However, the existence of harmony rules which relate root pitch to pulse (e.g. the penultimate rule in Table 5.2) suggests that rhythm information might improve the performance of the root pitch PUSSes.

A3.4. CONCLUSIONS

The finding (of the preceding section) that Bach harmonizes identical 5-note (skeletal) melody fragments with the same penultimate root pitch 80% of the time in Chorales 1 to 6 was checked to see if the trend applies in a further 26 chorales. This was not found to be the case, and so it was concluded that the root pitch progressions in Bach's chorale harmonizations are not as recurrent as we had hoped, supported by Lovelock's (1970) observations (listed in Section 5.5.3).

The experiment described in this Appendix has used a context-based approach. Such an approach differs appreciably from the statistical methods employed elsewhere (e.g. Whitney, 1975). The author believes that statistical approaches are more likely to "average away" the unusual features of a piece of music that give it its particular charm. By exploring the musical context in which particular melodies and root pitches occur in a composer's music (using PUSSes for example), aspects of that composer's style can be analysed in a way that takes these unusual features into account.
During the preparation of this thesis for printing, the author has become aware of the following recent developments. Kuhn (1976) has extended his aural training programs (see Kuhn, 1974) to adapt to student errors. The method of adaptation is not described by Kuhn.

Zaripov (1975) has developed programs which indicate errors in student harmony. However, his programs do not supply the constructive criticism provided by the alternative harmonization based on the students' work, as described in Chapter 4.

A program for key-determination which uses cues in the melody has been developed by Holtzman (1978). This program is restricted to melodies only. By not dealing with harmony or modulations, its scope is more limited than the analysis programs described in Chapter 4.
REFERENCES


COPÉRIN, (1717) L'art de Toucher le Clavecin. The Art of Playing the Harpsichord. Trans. by M. Roberts and republished by Breitkopf und Hartel, Wiesbaden, Germany.


SHAFFER, H. (1978) Personal communication with the author.


The concluding pages list papers used by the author but not specifically referred to in the text. They are grouped under the following headings:

- Musical instruments and performance
- Psychoacoustics and the ear
- Mathematics and music
- Education
- Music instruction
- Sound synthesis
- Composition
- Music display
- Analysis and Transcription Codes
- Harmony, Tonality and Analysis

MUSICAL INSTRUMENTS AND PERFORMANCE


"Why do rhythms and melodies, which are mere sounds, resemble dispositions, while tastes do not, nor yet colours or smells?"

Aristotle (384-322BC)
PSYCHOACOUSTICS AND THE EAR


MATHEMATICS AND MUSIC


EDUCATION


MUSIC INSTRUCTION


SOUND SYNTHESIS


HIRST,G. AND GOLDSCHLAGER,L. (1975) MONHIT/Player 2.4 A computer music-playing system. Published by Department of Eng Physics, Research School of Physical Sciences, ANU, Canberra.


COMPOSITION


MUSIC DISPLAY


"The fact is, there are no rules, and there never were any rules, and there never will be any rules of musical composition except rules of thumb: and thumbs vary in length, like ears."

HARMONY, TONALITY AND ANALYSIS


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