7

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Memory and Attention in Music

MEMORY IN MUSIC

It is clear from general considerations that musical memory must involve a highly complex and differentiated system, where information is retained simultaneously at many levels of abstraction. A detailed investigation of this system is only just beginning; and so far it has focussed almost exclusively on memory for pitch, or for abstractions based on pitch information. This chapter reviews the current state of knowledge in the field. The first part examines the organization of the pitch memory system: and the second part describes the various ways in which pitch information is recoded, and so retained in parallel.

Organization of the Pitch Memory System

Various hypotheses may be advanced concerning the influences acting on pitch memory in storage. We may suppose, for instance, that such memory simply decays with time; or alternatively that pitch information is retained in a general system which is limited in terms of the number of items it can hold simultaneously. Another suggestion is that such information is retained in a specialized system, whose elements interact in specific fashion.

That time alone produces a decrement in memory for pitch has indeed been observed. When subjects are asked to make pitch comparison judgments between two temporally separated notes, such judgments become increasingly blurred as the time interval between the notes increases (Koester, 1945; Harris, 1952; Bachem, 1954, Wickelgren, 1969). However, memory decays only very gradually as a function of time alone. In the study by Harris (1952) subjects made pitch recognition judgments involving tonal stimuli of around 1000 Hz. After a retention interval of 15 seconds, the frequency discrimination threshold was still as good as 8 Hz. To place this in a musical context, a semitone in this frequency range is about 60 Hz; so the amount of memory blurring over this time period is small indeed.

In M. Critchley and R.A. Henson (Eds.)
Music and The Brain, 1977, Heinemann

On the other hand, a substantial decrement in pitch recognition occurs when other notes are interpolated during the retention interval. This impairment results even when instructions are given to the subjects to ignore the interpolated notes. An experiment which demonstrates this effect was performed by Deutsch (1970a). Subjects were selected for obtaining a score of 100 per cent. correct in comparing pairs of notes which were separated by a silent interval of six seconds, and which were either the same in pitch or which differed by a semitone. The same note pairs were then again presented; except that now eight notes were interpolated during the retention interval. The subjects were instructed to listen to the first test note, to ignore the eight interpolated notes, and then to judge whether the second test note was the same in pitch as the first or different. It was found that the interpolated notes produced a substantial decrement in recognition performance. The subjects, having achieved an errorless performance in the condition with no interpolated notes, now produced an error rate of over 40 per cent. Here a score of 50 per cent. correct represented chance performance; so the eight interpolated notes almost obliterated the subjects' ability to detect a pitch difference of a semitone.

We may now inquire why the interpolated notes produce a memory loss. One might hypothesize that these notes distract the listener, and so impair his ability to concentrate on the note he is trying to remember. If this interpretation were correct, then other interpolated materials which produced distraction of attention would have the same effect. Alternatively, we might suggest that there is a general memory store into which the pitch information is entered along with other information; and that this store is limited in terms of the amount of information it can accommodate. If this were so, then other interpolated materials which were also remembered should again impair pitch recognition. Yet another hypothesis is that information concerning pitch is retained in a specialized system. We might then expect that memory disruption would occur if other notes were interpolated, but not if different types of material were interpolated instead.

These various hypotheses were put to experimental test (Deutsch, 1970b). Subjects made pitch recognition judgments under three different conditions. In the first condition the subjects were asked to recognize a note following a retention interval of five seconds during which six notes were interpolated. In the second condition, instead of six notes, six spoken numbers intervened between the notes to be compared. These numbers were adjusted to appear equal in loudness to the notes, and they were spaced identically. In both these conditions, the subjects were asked to judge whether the test notes were the same or different in pitch, and to pay no attention to the intervening items. In the third condition, numbers again were interpolated, and the subjects were asked to recall them besides making the pitch recognition judgment. This ensured that the numbers had been attended to, and had entered memory.

The results of this experiment are shown on Table 1. It can be seen that the interpolation of notes caused a substantial decrement in pitch recognition; however, only a minimal decrement occurred when spoken numbers were interpolated, even when these numbers were also recalled. It will also be noted that number-recall when subjects were required to make pitch comparison judgments was as good as in a control condition where this requirement was waived. It seems clear from this experiment that the memory decrement due to interpolated notes is not based on attention distraction, nor on displacement of material in some general memory store of limited capacity. We may therefore conclude that there exists a specialized system for the retention of pitch information.

Table 1

	Percentage errors	
Condition	*Pitch recognition*	*Number recall*
1. Pitch recognition with intervening notes ignored	32·3	
2. Pitch recognition with intervening numbers ignored	2·4	
3. Pitch recognition with intervening numbers recalled	5·6	25·3
4. Number recall with no pitch recognition required		27·4

Percentage errors in pitch recognition as a function of type of material interpolated during the retention interval. Number recall was scored correct on any trial when all the numbers were recalled in the correct order. (From Deutsch, 1970b.)

Further experiments were addressed to uncovering the properties of the pitch memory system. One might still hypothesize that this system is one of limited storage capacity, except that it accepts only pitch information. On this theory, memory impairment would result from an overload produced by introducing too many notes. If this were correct, then the amount of memory impairment produced by an interpolated note would not vary as a function of its relationship to the note to be remembered. However, if one note can be shown to have a specific effect on memory for another depending on their pitch relationship, then this would suggest a system in which pitch memory elements interacted in a specific manner.

An experiment was therefore made to study the effect on pitch memory produced by a note which formed part of a sequence interpolated between two notes to be compared for pitch, when its relationship to the note to be remembered varied systematically along the pitch continuum (Deutsch, 1972a). Subjects compared for pitch two notes which were separated by a five-second retention interval during which six other notes were played. Errors were plotted as a function of the pitch of a further note, which was placed in the second serial position of the intervening sequence, the relationship of which to the first test note varied from identity to a whole tone separation on the equal tempered scale. All other notes in the intervening sequence were at least $1\frac{1}{2}$ tones removed from the first test note. In a baseline condition no critical note was interpolated, and the note in the second serial position was chosen in the same way as the other notes in the intervening sequence.

Figure 1 plots error rates in pitch recognition judgment as a function of the pitch relationship between the first test note and the critical interpolated note. As can be seen, the disruptive effect of one note on memory for another does indeed vary as a function of their pitch relationship. This variation can be summarized in the following manner: memory is facilitated when the critical interpolated note is identical in pitch with the first test note. As the pitch difference between the first test note and the critical interpolated note increases, errors also increase. This increase peaks at $\frac{2}{3}$ tone separation, and then at distances greater than $\frac{2}{3}$ tone errors decrease again, reaching a baseline at around a whole tone separation. This experiment shows therefore that impairment in pitch memory occurs as a property of a processing mechanism which is organized in a precise and systematic manner. The functioning of such a system cannot be explained on the grounds of simple and undifferentiated storage capacity limitation.

A further experiment systematically explored the disruptive effect on pitch recognition which was produced by including within an interpolated sequence a note which was a semitone removed from the note to be remembered (Deutsch, 1973a). As shown in Table 2, when the test notes were identical in pitch, including a note which was either a semitone higher or a semitone lower produced roughly the same increment in errors. A substantially larger increment was produced when both these notes were included. When the test notes differed in pitch by a semitone, including a

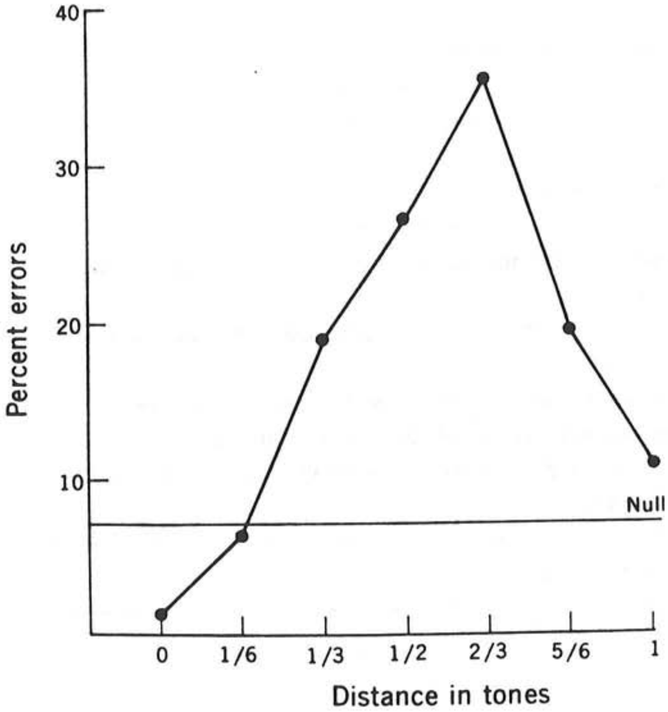


Figure 1 Per cent. errors in pitch recognition judgment as a function of the pitch relationship between the first test note and a critical interpolated note. The line labelled "Null" shows per cent. errors where no note in the critical range was included in the interpolated sequence. (From Deutsch, D., 1972, by permission of *Science,* **175**, 1020–1022. Copyright 1972 by the American Association for the Advancement of Science.)

note a semitone removed from the first test note also caused an increase in errors. However, a substantially greater increase occurred when the critical interpolated note happened to be identical in pitch to the second test note. (This effect appears to be due to deterioration of temporal or order information and this is discussed below.) And again, including both such notes produced a greater increase in errors than including either one alone. It was further found (Deutsch, 1975a) that when the test notes were identical in pitch, and a note that was a semitone higher or lower was included in a sequence of six interpolated notes, the disruptive effect was roughly constant whether the critical note was placed in the second or in the fifth serial position of the intervening sequence (Figure 2).

Such findings led to the construction of a theoretical model for the organization of pitch memory elements (Deutsch and Feroe, 1975). On this

Table 2

Condition	*Percentage errors*
TAPE I	
A. Test notes same	
1. Note a semitone higher included in intervening sequence.	7·9
2. Note a semitone lower included in intervening sequence.	6·9
3. Two notes, one a semitone higher and the other a semitone lower, included in intervening sequence.	18·5
4. No note a semitone higher or lower included in intervening sequence.	2·8
B. Test notes different	7·5
TAPE II	
A. Test notes different	
1. Note of the same pitch as the second test note included in intervening sequence.	20·1
2. Note a semitone from the first test note, but on the opposite side of pitch continuum to the second test note, included in intervening sequence.	7·4
3. Two notes, one as in Condition 1 and the other as in Condition 2, included in intervening sequence.	25·2
4. No note a semitone removed from the first test note included in intervening sequence.	3·2
B. Test notes same	6·6

Percentage errors in pitch recognition as a function of the presence in the intervening sequence of either one or two notes which were a semitone removed from the first test note. Tape I studied the effect in sequences where the test notes were identical in pitch, and Tape II where the first and second test notes differed by a semitone. (From Deutsch, 1973a.)

model, pitch memory is the function of an array the elements of which are activated by notes of particular pitch. These elements are placed along the array in such a way that elements which are activated by notes separated by the same distance in log frequency units are also separated by the same distance along the array. The hypothesis also proposes that these elements are linked as a recurrent lateral inhibitory network, analogous to those investigated by neurophysiologists in systems handling incoming sensory information (Ratliff, 1965).

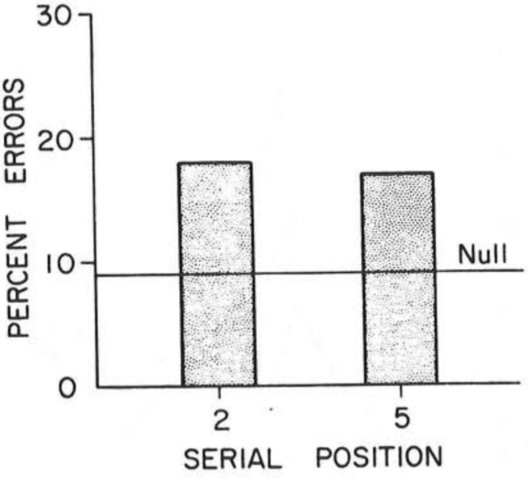


Figure 2 Per cent. errors in pitch recognition judgment where the first and second test notes were identical in pitch, and a note a semitone higher or lower than the test notes was included in the interpolated sequence. Errors are plotted separately for sequences where the critical interpolated note was placed in the second and the fifth serial position of a sequence of six interpolated notes. The line labelled "Null" shows per cent. errors in sequence where no such critical note was interpolated. (From Deutsch, 1975a.)

This hypothesis makes a specific prediction which would not be expected on other simple models. Thus, if a note which is inhibiting another note in memory were itself inhibited, this should release the originally inhibited note from inhibition. Such a phenomenon of disinhibition has been shown by neurophysiologists in sensory arrays. Applying such a model to the study of memory suggests that the inhibition of the inhibiting note would actually cause memory for the test note to return.

An experiment was carried out to test this prediction. Subjects compared for pitch two notes which were separated by a sequence of six interpolated notes. There was always placed in the second serial position of the intervening sequence a note which was $\frac{2}{3}$ tone removed from the first test note. Errors were then plotted as a function of a further note, placed in the fourth serial position, the relationship to the note in the second serial position varying systematically from identity to a whole tone separation. As shown in Figure 3, a systematic return of memory was indeed obtained. The error rate when the note in the fourth serial position was $\frac{2}{3}$ tone

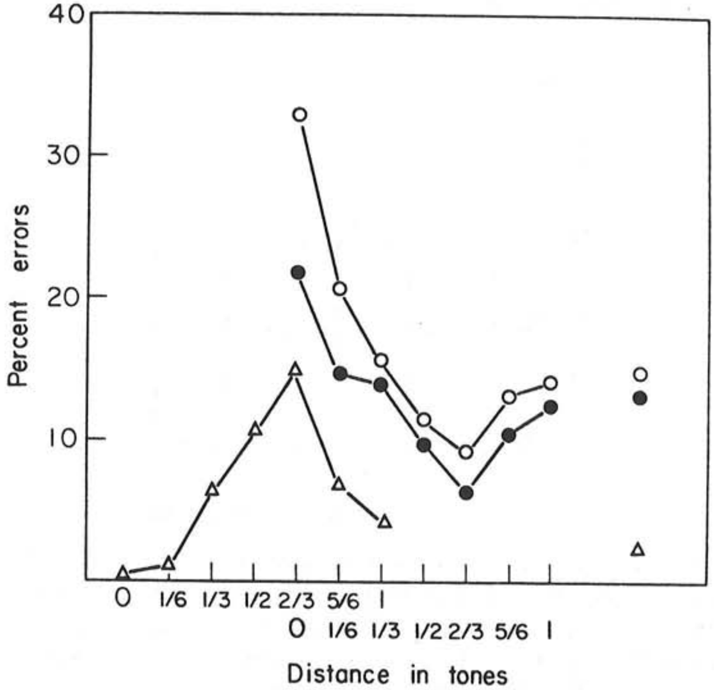


Figure 3 Per cent. errors in pitch recognition obtained experimentally and predicted theoretically. Open triangles display per cent. errors in the baseline experiment which varied the pitch relationship between a test note and a critical interpolated note. (Open triangle at right displays per cent. errors where no notes were interpolated in the critical range under study.) Filled circles display per cent. errors in the experiment where a note which was $\frac{2}{3}$ tone removed from the test note was always interpolated. Errors are plotted as a function of the pitch relationship between this note and a second critical interpolated note which was further removed along the pitch continuum. Open circles display per cent. errors for the same experimental conditions predicted theoretically from the lateral inhibition model. (Filled and open circles at right display per cent. errors obtained experimentally and assumed theoretically where no further critical note was interpolated.) (From Deutsch, D., and Feroe, J., 1975, by permission of *Perception and Psychophysics*, **17**, 320, 324. Copyright 1975 by the Psychonomic Society, Inc.)

removed from the note in the second serial position was significantly lower than in the baseline condition where the note in the fourth serial position was outside this range. A first-order inhibitory function was also obtained, using subjects selected by the same criterion as for the disinhibition experiment. This was used to calculate the theoretical disinhibition function, so that it could be compared with the function produced experimentally. These functions are also portrayed in Figure 3. It can be seen that there is a correspondence between the theoretically and empirically derived disinhibition functions. This is therefore strong evidence that the elements of the pitch memory system are arranged as a lateral inhibitory network, analogous to those handling sensory information at the incoming level.

Octave generalization

So far we have discussed interactive effects occurring in memory between notes which are separated by less than an octave. However, it becomes clear for many reasons that we code pitch not only along a monotonic dimension of "height" but also in terms of its position within the octave. We may therefore ask whether these interactive effects take place simply along a monotonic pitch continuum, or whether an abstracted octave array is also involved.

In one experiment (Deutsch, 1974a), subjects compared two notes for pitch when these were separated by a sequence of eight interpolated notes. The interpolated notes in any one sequence were either all in the same octave as the test notes; or they were all in the octave above; or in the octave below; or half were in the octave above and the other half in the octave below, the order of octave placement being random. Figure 4 shows how the rate of error varied for the different conditions. Interpolated notes in the lower octave produced fewest errors. Notes in the higher octave brought about an intermediate number of errors; whereas notes in the middle octave were responsible for an even greater number of errors. However, the mixed condition produced the most disruption. This study therefore demonstrates that accuracy in pitch recognition in a sequential setting depends upon the octave or octaves in which the other notes are placed.

We can also inquire what effect octave displacements have on specific disruptive effects in pitch memory. To this end, Deutsch (1973b) investigated two specific effects. The first occurs when the test notes are the same in pitch, and a note which is a semitone higher or lower is included in the interpolated sequence (Deutsch, 1973a). When both such notes are included this disruptive effect is substantially enhanced (Table 2); so this condition was studied here. A second disruptive effect occurs when the test notes differ in pitch, and a note which is identical with the second test note is included in the intervening sequence. Here the subject tends to misrecognize the second test note as the same as the first (see below). The question investigated was whether such disruptive effects also occur when the critical interpolated note or notes are displaced by an octave.

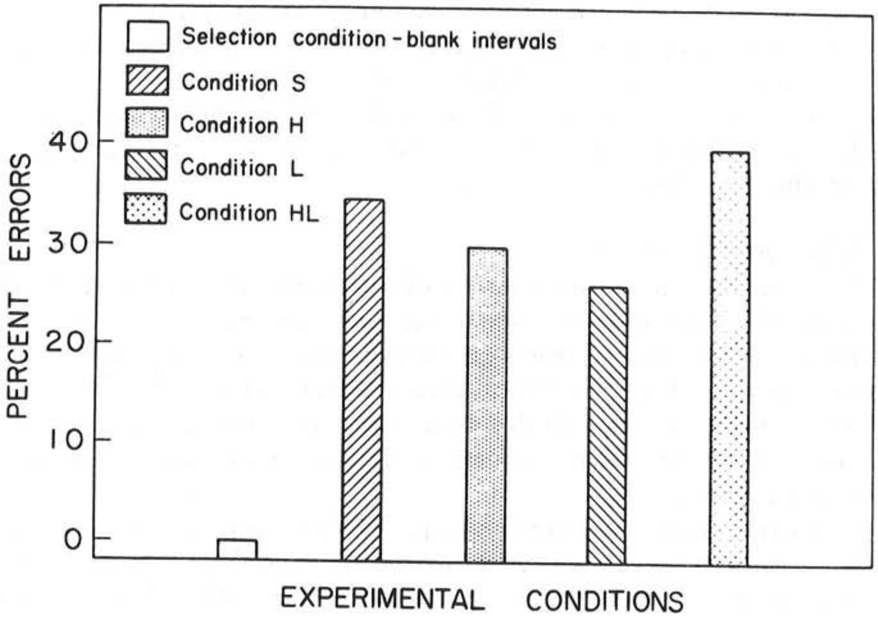


Figure 4 Per cent. errors in pitch recognition as a function of the octave in which the interpolated notes were placed. All sequences contained eight interpolated notes. Condition S: interpolated notes placed in the same octave as the test notes. Condition H: interpolated notes placed in the octave above. Condition L: interpolated notes placed in the octave below. Condition HL: half of the interpolated notes placed in the octave above and the other half in the octave below; the order of octave placement being random. (From Deutsch, 1974a.)

Table 3 illustrates the results of this experiment. It can be seen that both types of disruptive effect exhibit octave generalization. However, significant differences in the degree of these effects were found depending on the octave in which the critical interpolated notes were placed. When the critical interpolated notes were placed in the higher octave, then the disruptive effects were almost as great as when they were placed in the middle octave. However, when the critical interpolated notes were placed in the lower octave the disruptive effects were much weaker. From an analysis of the pattern of errors, it was concluded that these effects take place along both a monotonic pitch continuum, and also along an abstracted octave array.

Repetition effects

Substantial effects on memory performance are produced by including in an interpolated sequence notes of the same pitch as one or other of the notes to be compared. Such effects may be either facilitary or disruptive.

Table 3

Condition	*Percentage errors*
Test notes different	
1. No note at pitch of the second test note, or displaced by an octave from this note, included in intervening sequence.	4·6
2. Note at pitch of the second test note included in intervening sequence.	26·7
3. Critical included note as in Condition 2, but displaced on an octave higher.	20·2
4. Critical included note as in Condition 2, but displaced an octave lower.	12·1
Test notes same	
5. No note a semitone removed from the test note, or displaced from such a note by an octave, included in intervening sequence.	5·6
6. Two notes, one a semitone higher than the test note, and the other a semitone lower, included in intervening sequence.	24·4
7. Critical included notes as in Condition 6, but displaced an octave higher.	21·0
8. Critical included notes as in Condition 6, but displaced an octave lower.	11·3

Percentage errors in pitch recognition as a function of the presence in the intervening sequence of notes displaced by an octave from those known to produce disruption. (From Deutsch, 1973b.)

If a note of the same pitch as the first test note is included among the interpolated notes, an improvement occurs in the recognition performance, which is highly sensitive to the serial position of the repeated note. In one experiment, subjects judged whether two test notes were the same or different in pitch when they were separated by a sequence of six interpolated notes (Deutsch, 1975b). It was found that when a note of the same pitch as the first test note was included in the second serial position of the intervening sequence, there resulted a substantial and highly significant improvement in performance. However, when the repeated note was placed in the fifth serial position, this improvement was insignificant. This was true both for sequences where the test notes were identical in pitch, and also where they differed (Figure 5).

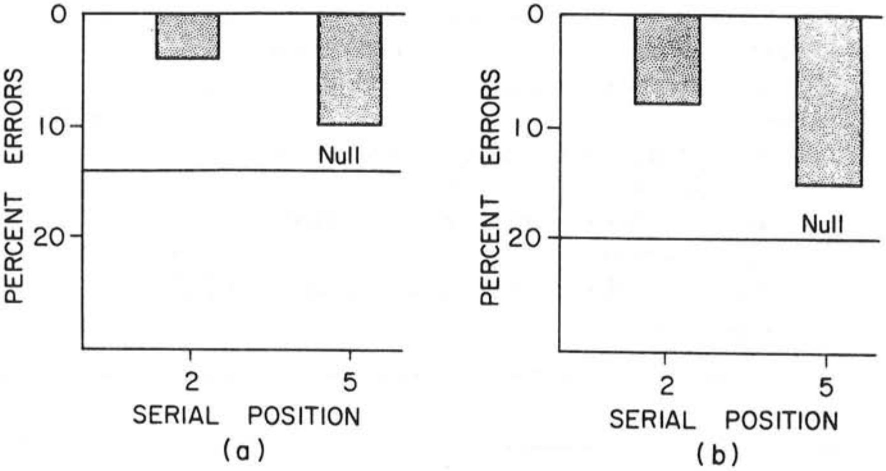


Figure 5 Per cent. errors in pitch recognition when a note of the same pitch as the first test note was included in the interpolated sequence. Errors are displayed separately for sequences where the repeated note was placed in the second and the fifth serial position of a sequence of six interpolated notes. The lines labelled "Null" display per cent. errors in sequences where the first note pitch was not repeated. (a) First and second test notes identical in pitch. (b) First and second test notes differed in pitch by a semitone. (From Deutsch, 1975b.)

A great increase in errors is produced in sequences when the test notes differ in pitch, and when a note that is identical in pitch to the second test note is included in the interpolated sequence. This effect depends largely upon the serial position of the repeated note: a far greater increase in errors occurs when this note is placed in the second serial position of a sequence of six interpolated notes than when it is placed in the fifth serial position

(Figure 6). However, no serial position effect is apparent in sequences where the test notes are identical in pitch, and where one of the interpolated notes is a semitone removed (Figure 2).

Such repetition effects are probably due to the deterioration of information along a time or order continuum. Deutsch (1972b) proposed an explanation for such effects and the way they vary with serial position.

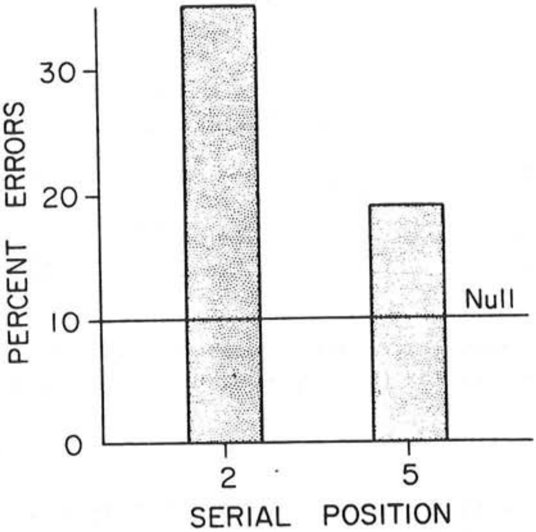
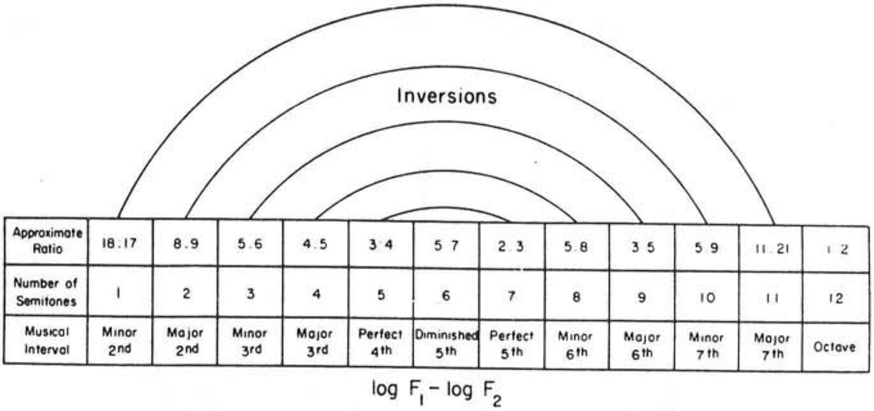


Figure 6 Per cent. errors in pitch recognition where the test notes differed in pitch by a semitone, and a note of the same pitch as the second test note was included in the interpolated sequence. Errors are displayed separately for sequences where the critical interpolated note was placed in the second and the fifth serial position of a sequence of six interpolated notes. The line labelled "Null" displays per cent. errors in sequences where no such critical note was included. (From Deutsch, 1975a.)

Other systems

Although little formal investigation has been made into the influences acting on other musical attributes in storage, it is tempting to speculate that the principles uncovered in the case of pitch also hold for other attributes. In the case of simultaneous and successive intervals, for instance, we may speculate that such memory is the function of a continuum the elements of which are activated by the simultaneous or successive presentation of tone pairs (Figure 7). We may further imagine that such elements are arranged according to the size of the ratio between the component frequences (i.e. in units of log F_1–log F_2), and that specific facilitative and disruptive effects take place between elements along this continuum, analogous to effects found in absolute pitch memory. Because of the perceptual similarity of simultaneous intervals which are inversions of each other (see below), we would expect to find scallops in the curves plotting such interactive effects in the case of simultaneous note pairs. At present, however, this can only be proposed quite tentatively, and further work might yield interesting results.



Approximate Ratio	18:17	8:9	5:6	4:5	3:4	5:7	2:3	5:8	3:5	5:9	11:21	1:2
Number of Semitones	1	2	3	4	5	6	7	8	9	10	11	12
Musical Interval	Minor 2nd	Major 2nd	Minor 3rd	Major 3rd	Perfect 4th	Diminished 5th	Perfect 5th	Minor 6th	Major 6th	Minor 7th	Major 7th	Octave

Figure 7 The interval size continuum. This is here divided into semitonal steps for purposes of clarity, but these steps simply represent arbitrary increments along the continuum.

Higher-level encoding of pitch information

For most persons, absolute levels of performance in pitch recognition are remarkably poor (Pollack, 1952, 1964; Deutsch, 1970a, 1970b). Memory for pitch information must therefore depend largely upon abstraction of this information and its retention in recoded form. We shall therefore discuss the various ways in which such recoding is achieved.

At the first level of abstraction pitch information is coded as a set of features. Two types of encoding will be considered here in detail. The first designates the position of a note within the octave, and the second abstracts the relationships between units of a combination of pitches.

Octave equivalence

Notes with waveform frequencies standing in the ratio of 2 : 1 are defined as an octave apart, and a perceptual similarity exists between notes which are separated by an octave or octaves. Generalization of response to notes separated by octaves has been demonstrated in conditioning situations, in both man and animals (Humphreys, 1939; Blackwell and Schlosberg, 1943). Moreover, those with absolute pitch may often relegate a note to the wrong octave, even though they name it correctly (Baird, 1917; Bachem, 1954).

The principle of octave equivalence forms an important basis for the traditional musical scale. This is composed of a set of notes within the octave, each of which is given a name (C, C♯, D, etc.); and the entire scale consists of the repetitive presentation of these notes across successive octaves. Octave duplications in scales also occur cross-culturally, and the principle of octave equivalence may be regarded as a universal musical phenomenon (Nettl, 1956).

Interval and chord equivalence

When two notes are presented either simultaneously or in succession, a musical interval is perceived; and a perceptual similarity exists between intervals with component notes separated by the same frequency ratio. This principle forms part of the basis for the traditional musical scale, the smallest unit of which is the semitone, representing a frequency ratio of 18: 17. Note-pairs separated by the same number of semitones are considered as standing in the same relationship, and are given the same name in musical terminology. Figure 7 shows the set of intervals used in the traditional musical scale, together with their approximate frequency ratios. Attneave and Olson (1971) demonstrated under laboratory conditions that when subjects are asked to transpose a well-known melody, they do so by preserving the ratios between the successive notes. Further, examination of music in other cultures leads to the conclusion that such behaviour is not culture-dependent (Nettl, 1956).

The abstraction of relationships between simultaneously presented notes is not confined to note-pairs. We also classify together chords consisting of three or more notes; and chords with components standing in the same relationship are given the same name (major triad, minor triad, and so on). However, a chord cannot be defined simply in terms of the sum of its component intervals. For instance, a major triad and a minor triad sound quite different, yet in both cases their components stand in the relationships of a major third, a minor third, and a fifth (Figure 8). Thus the abstraction of chords consisting of three or more components involves more than the process of abstracting their component intervals.

In the case of simultaneous intervals and chords, a second shape recognition operation is also performed, known as inversion. Two chords are considered harmonically equivalent when their component notes are placed in different octaves. Thus, a simultaneous note-pair forming an interval of n semitones is perceptually similar to a pair forming an interval of 12-n semitones. The sets of note-pairs which are related by the operation of inversion are designated in Figure 7.

Experimental evidence for the perceptual similarity of inverted note-pairs was provided by Plomp et al. (1973). They required subjects to identify the intervals formed by simultaneous pairs of notes, and found that confusions occurred between intervals which were musical inversions of each other. For instance, more confusions occurred between fifths and fourths than between either with diminished fifths. Confusions between seconds and sevenths were also common. Further evidence was provided by Deutsch and Roll (1974) who required subjects to make pitch comparison judgments when the notes to be compared were accompanied by other notes of lower pitch. When the test notes differed but formed the same interval, errors in recognition were quite pronounced. A significant increase in errors was also found when the relationship formed by the first test combination (a musical fifth) was an inversion of the relationship formed by the second test combination (a musical fourth). It was concluded that errors were due to the perceptual equivalence of the inverted interval.

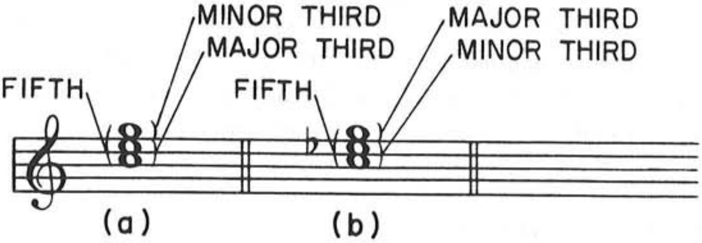


Figure 8 Root forms of the C major triad (a) and C minor triad (b); and their component intervals. In both cases, the components stand in a relationship of a major third, a minor third, and a fifth. However, in the major triad the major third lies below the minor third; and in the minor triad the minor third lies below the major third. (From Deutsch, 1969.)

The abstraction of specific features derived from pitch is analogous in many respects to the abstraction of spatial features in vision. There is good evidence that such abstractions in the visual system are achieved by a convergence of first-order units on to higher-order units, which in turn converge on to still higher-order units, and so on (Hubel and Wiesel, 1962). Deutsch (1969) proposed a mechanism for abstraction of features derived from pitch based on this principle of successive levels of convergence. Fundamentally, it assumes that pitch information is abstracted along two parallel channels, each of which consists of two levels of convergence. The first channel is concerned with abstraction of relational features. Here it is assumed that first-order units responding to notes of specific pitch are linked in groups of two and three to second-order units. These units therefore respond to specific intervals and chords. Three classes of such second-order units are defined: those responding to simultaneous stimulation only, those responding to ascending intervals, and those responding to descending intervals. These second-order units are then linked to third-order units in such a way that all units activated by notes standing in the same relationship are joined. Thus all units activated by thirds would feed on to one unit, all activated by fourths on to another, all activated by a major triad on to another, and so on. These third-order units therefore respond to abstracted intervals and chords (Figure 9).

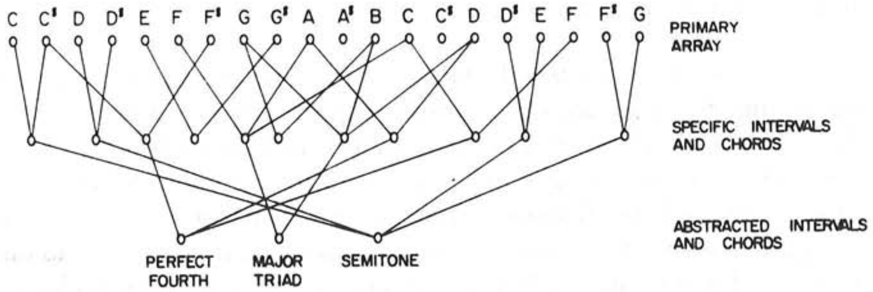


Figure 9 Two stages of abstraction along the transposition channel. Although units in the primary array are identified for purposes of clarity by musical notation, it is assumed that intervening units also exist, and that these are linked together in the same fashion. (From Deutsch, 1969.)

The second channel abstracts information concerning the position of a note within the octave, and also mediates inversion of chords. Here it is assumed that first-order units responding to notes of specific pitch are linked in such a way that there is convergence of notes separated by octaves on to the same second-order unit. In the second stage of transformation these units are linked to third-order units. It is assumed that these third-order units are activated by simultaneous rather than successive stimulus presentation. These units therefore underlie the perceptual equivalence of simultaneous intervals which are inversions of each other (Figure 10).

Contour

There is good evidence that we recognize a melodic sequence, not only

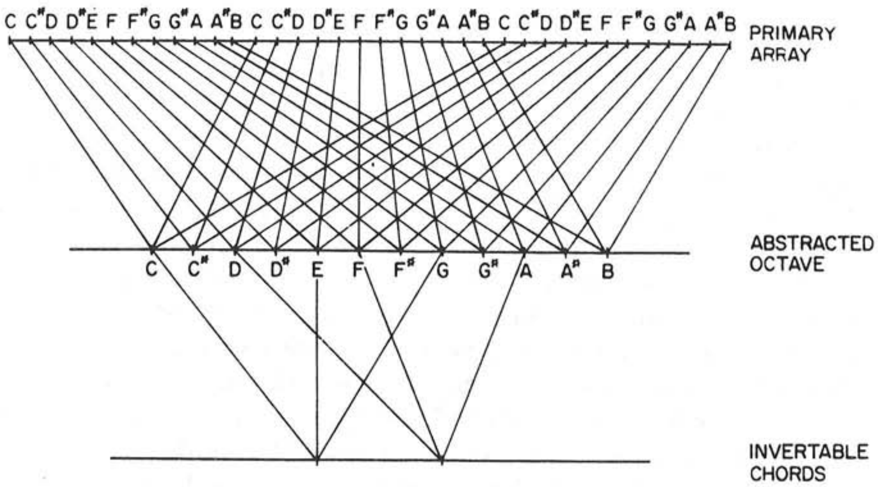


Figure 10 Two stages of abstraction along the octave channel. As in Figure 9, it is assumed that units intervening between those displayed here are also linked together in this fashion. (From Deutsch, 1969.)

because of its specific intervals, but also by global cues, such as its pitch range, and the sequence of directions of pitch change. Werner (1925) showed that people were able to recognize melodies when they were transformed on to extremely small scales, so that the interval sizes were grossly distorted. Furthermore, White (1960) found that melodies were recognized with fair accuracy when all the interval sizes were set to one semitone, leaving intact only the sequence of directions of pitch change. Indeed, in actual music a phrase is often transposed with distortion in the interval sizes, so as to conform to the elements of the scale; and such transposition is easily recognized (Figure 11).

Scales and modes

In the music of any given culture, melodic and harmonic sequences are composed out of small sets of pitch relationships, which are said to constitute their scale. The set of notes on the scale thus provides an alphabet in terms of which a melody or harmonic sequence may be defined. Thus transposition in a short-term situation often takes place along the scalar alphabet, so that the relative positions of the elements along the scale are preserved, but the intervals are therefore distorted (Figure 11).

For any given scale, one can determine a hierarchy of *a priori* probabilities of occurrence for notes standing in various positions along the scale. For instance, the note which occurs with greatest frequency is generally the tonic. In addition, one can determine a set of *transitional*

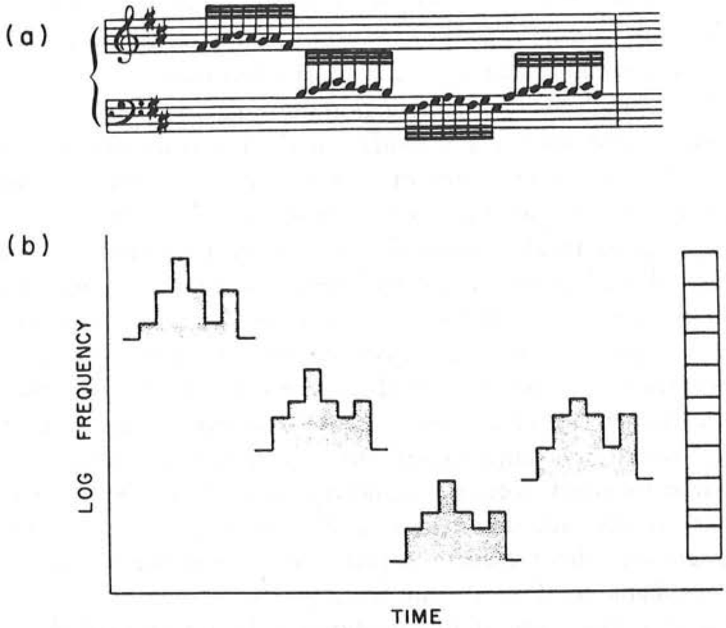


Figure 11 Transposition along the alphabet of the scale. A given melodic configuration is presented four times in succession, at different positions along the scale. Since the scale has unequal intervals, there results a variation in the set of intervals involved. (a) The sequence in musical notation. (b) The sequence plotted as log frequency versus time. The ladder at right displays the scale. (From Bach, J. S., *The Well-Tempered Clavier, Book I, Fugue V.*)

probabilities between the different elements of the scale. Thus in Western traditional music the leading tone is most often followed by the tonic, and so on. When the same set of pitch relationships is used as the basis for a different set of *a priori* and *transitional* probabilities, the scale is said to be in a different mode. Thus if we take the set of white notes on the piano and play them in ascending order, starting each time with a different note, the scales thus formed are in different modes (Scholes, 1950).

When we hear a piece of music, we quickly become sensitive not only to its scale, but also to the set of *a priori* and *transitional* probabilities for the elements of the scale. This is true both for linear successions of notes, and also for harmonic sequences. In traditional Western harmony there are strong *transitional* probabilities governing the root progressions of chords. For instance, the chord on the tonic (I) is most often followed by the chord on the subdominant (IV) or dominant (V); sometimes by the chord on the submediant (VI) and less often by the chord on the supertonic (II) or mediant (III) (Piston, 1948). At a higher organizational level, when modulating to a different key, the most probable modulations are to the dominant, subdominant, or relative major or minor.

The mapping of pitch information on to scales with strong *a priori* and *transitional* probabilities is of fundamental importance to musical memory, as it enables us to make use of a fund of highly learned information in recalling or recognizing a given sequence. The differences between attempting to recall a musical sequence in a familiar tonal system as compared with a set of notes chosen at random, is equivalent to the difference between trying to recall a sentence as compared with a set of nonsense syllables. Indeed, it has been demonstrated experimentally that short-term recognition of melodic patterns is greater when the melodies are in our tonal system than when they are not (Francés, 1972; Zenatti, 1969). Moreover, recognition of a melodic sequence which is preceded and followed by other notes is enhanced when the context notes establish a tonality (Miller and Cuddy, 1972). Recognition is greatest if the context notes are such that the entire sequence resolves to the tonic, which is the most probable resolution in our tonal system.

It is interesting to recall that modern serial music discards the traditional framework of probability relationships. Instead, every composition includes all twelve tones of the chromatic scale. For any given composition a particular ordering is adopted of these twelve semitones (known as the basic set, or row); and the entire harmonic and melodic material of the piece is drawn from this row, which may, however, be transposed, inverted or reversed according to the wishes of the composer. Thus each piece of music establishes its own set of *transitional* probabilities, and there is no set for this style of music in general. This necessarily imposes a much greater burden on memory than exists for tonal music (see also Meyer, 1967).

Recognition of melodic sequences under various transformations

A question of importance to musical memory concerns the extent to which a melodic sequence will be recognized when it has been subject to a given transformation. The case of transposition is clear. Here the entire sequence is presented in a different pitch range. Transposition takes place so readily that it is much easier to recognize a well-known tune than to determine in what key it is being played. Within a given piece of music transposition occurs in two different ways. First, the entire scale may be transposed, so that the set of intervals between successive tones is preserved. Or the sequence may be shifted along the scale so that the relative positions of the elements are preserved, but the pitch relationships are distorted. Figure 11 shows the same sequence repeated at four different pitch levels, involving three different set of intervals.

Other transformations used in music are known as inversion and retrogression. Inversion constitutes a systematic reversal of the directions of the successive intervals (this is different from the harmonic use of the term described above). In other words, all ascending intervals become descending intervals, and vice versa. Retrogression constitutes a reversal of the order in which the components of the sequence are presented. Musicians disagree widely on the question of perceptual equivalence of melodies transformed by these operations. This is particularly true of retrogression. Thus Piston (1949) wrote: "Retrograde forms are rarely employed since it is very difficult for the ear to recognize a motive played in this fashion" and described the canon in retrograde motion as "more an intellectual stunt than a purely musical effect." And Tovey (1957) wrote that retrogression "is of extreme rarity in serious music." However, Schoenberg (1951) took a different view. Drawing an analogy between inversion and retrogression in music, and inversion and mirror image reversal in visual shape perception, he said:

> *The unity of musical space demands an absolute and unitary perception*. In this space . . . there is no absolute down, no right or left, forward or backward. . . . Just as our mind always recognizes, for instance, a knife, a bottle or a watch, regardless of its position, and can reproduce it in the imagination in every possible position, even so a musical creator's mind can operate subconsciously with a row of tones, regardless of their direction, regardless of the way in which a mirror might show the mutual relations, which remain a given quantity.

Given this disagreement, the question of perceptual equivalence of inverted or retrograde sequences is of considerable practical interest to musicians, as well as of theoretical interest to psychologists. In one experiment Dowling (1972) presented subjects with a standard five-note melody, and then with a comparison melody. In one set of conditions the comparison melody was either an exact transposition of the first or it was an inversion, retrograde, or retrograde-inversion of the first (in retrograde-inversion both the operations of inversion and retrogression were performed on the sequence); or it was unrelated. In another set of conditions the comparison melody was still more distorted so that the exact intervallic relationships were destroyed although the contour was preserved. It was found that although recognition performance for the transformed sequences was above chance, the subjects did not appear to distinguish between exact transformations and those that preserved contour alone.

Another experiment with bearing on this question involved long term recognition memory (White, 1960). Subjects were required to identify well-known tunes which were transformed in various ways. It was found that when the tunes were played backwards, recognition was again above chance; however, it was at about the same level as when the sequences were presented with all the pitch information removed so that the rhythm provided the only cue. Furthermore, the tunes were recognized better when the intervals were permuted randomly than when they were systematically reversed. This strongly suggests that the subjects were recognizing the retrograde sequences on the basis of their component intervals, rather than their orders.

A further question involves the principles of octave equivalence. One might suppose that since notes standing in an octave relationship are perceptually similar under various conditions, melodic sequences would also be perceptually similar when their components are placed within different octaves. To test this hypothesis Deutsch (1972c) played the first half of the tune "Yankee Doodle" to subjects under a number of conditions, with each hearing only one item. This tune was recognized by all subjects when it was played in any one of three octaves. However, when each note was chosen at random from these same three octaves (with the restriction that no two successive notes were taken from the same octave), recognition was actually slightly worse than when the tune was played as a series of clicks with the rhythm alone remaining. Similar findings have recently been reported by Dowling and Hollombe (1976) with the use of several tunes.

Deutsch (1972c) also found that when subjects were informed of the identity of the tune, they were able to follow the scrambled octaves sequence, and confirm that each note was indeed correctly placed within its octave. It was suggested that the subjects were able to imagine the tune simultaneously with hearing the distorted version, and so match each note with its octave equivalent. In this case, such an operation could be meaningfully performed in music if memory for the sequence were strong enough; or if the structure of the sequence were such that the displaced note was highly probable.

Higher-level memory organization

The organization of music is essentially hierarchical. Notes combine to form phrases, which in turn form phrase-groups, which are in themselves successively combined until, at the highest level of the hierarchy, we obtain the composition's musical form (which often falls into one of those categories to which analysts give the name rondo, sonata, and so on).

Such hierarchical organization is important in retrieving musical information from memory. Experiments involving memory for many types of material, ranging from letters of the alphabet to patterns of lights, have demonstrated that retention is substantially improved if the material is hierarchically structured (Restle and Brown, 1970; Tulving and Donaldson, 1972).

Several theories of the organization of memory have assumed that information is retained along an internal hierarchy, and that it is retrieved by a systematic traversal of this hierarchy. This type of speculation can be usefully applied to music. However, it must be noted that cultivated music often involves the simultaneous presentation of several streams of notes. The information in each stream has its own structure, and the harmonic sequences produced by simultaneous notes are also systematically organized. An example of such multiple determinism is shown in Figure 12. In retrieving such information from memory several structures must be traversed in parallel; so it would be more useful to think of music in terms of multiple interacting hierarchies rather than a single hierarchy.

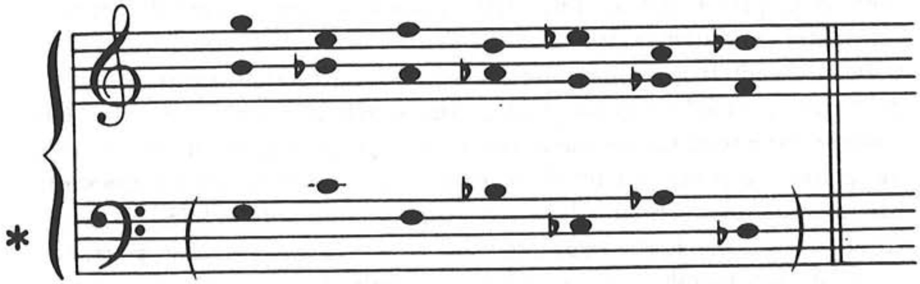


Figure 12 A complex musical sequence which is simultaneously determined by three types of progression. The top linear row may be described as a descending minor third repetitively transposed down a whole tone. The second linear row may be described as a descending run on the chromatic alphabet. And the harmonic sequence may be described as descending through the cycle of fifths. (From Fig. A1, Example 59, p. 168, of *Emotion and Meaning in Music* by L. B. Meyer. Copyright 1956 by the University of Chicago Press.) (* implied root progressions.)

Attention in music

In listening to music, we do not as a rule attend with equal emphasis to all incoming stimuli, but rather, we focus our attention in various ways. Our attention strategies may change according to the type of music being played. For instance, when a solo instrument plays a simple melodic line there is no competition for attention. In contrapuntal music such as canons or fugues, we attempt as far as possible to attend to the various streams simultaneously. However, it is likely that we perceive such music instead in a fashion similar to Rubin figures in vision, where we fluctuate between alternative modes of figure-ground organization, rather than perceiving several figures and no ground. In other music, such as accompanied songs, one part serves generally as the figure and the other part as the ground. But even there ambiguities often emerge, and figure and ground may reverse their positions. Certain *avant-garde* music of today aims simply at creating textures – to produce a continuous stream of sound where no figure clearly emerges.

Much selective listening to music is voluntary; or at least it appears to be. We have the impression that we can chose at will which type of information to attend to. However, certain sounds capture the attention more than others. Loud notes will be noticed rather than soft; high notes rather than low. A contrasting sound which emerges from a homogeneous background will command attention. Notes with sharp attacks will be noticed in preference to notes with gradual onsets. A sound which is constantly modulating, for instance a note with *vibrato*, or a drum roll, will stand out from sounds which are smooth. Certain instruments are deliberately tuned so as to produce beats, whose constant waxing and waning serve to maintain the attention. For instance, most of the notes on the piano are produced by three strings which are struck by the same hammer; and these are tuned each to a slightly different pitch (Kirk, 1959). Another example is the Indonesian *gamelan* which is tuned in pairs, the pitch of each member of a pair being slightly different. Finally, certain specific sounds, such as the human voice, appear to be particularly attention-compelling.

One central factor in musical attention is the formation of sequential groupings. That is, in listening to music in which more than one note is presented at a time, the listener groups these notes into sequential configurations, which then form channels of attention. Listening to such music therefore involves a continuous process of decision as to which successive note to link with which. An important experimental question therefore concerns how such linkages are formed.

This type of question has been extensively investigated in the case of listening to simultaneously presented verbal material. Egan et al. (1954) required listeners to identify one of two simultaneous messages, and examined the conditions which reduced interference from the unwanted message. They found that high-pass filtering (i.e. omitting the high-frequency components) of either the accepted or the rejected message substantially improved intelligibility. Differences in loudness also helped, especially when the wanted message was the louder. Spatial separation led to markedly improved performance. Indeed, even a small amount of spatial separation has been found useful in focussing attention on one of two simultaneous verbal messages (Spieth et al., 1954; Triesman, 1964). Other studies have shown that the semantic content of the two messages may be important in determining selection (Gray and Wedderburn, 1960; Yntema and Trask, 1963; Deutsch and Deutsch, 1963). This would have its counterpart in music in the set of *a priori* and *transitional* probabilities between notes (see above).

The technique most commonly employed in investigating selective attention to verbal materials is known as dichotic listening. Here two simultaneous sequences are presented through earphones, with a different sequence to each ear. The subject is then instructed in various ways; for instance, to report what he heard, or to attend selectively to one message rather than the other. By examining the subject's performance, one can explore the principles underlying the formation of attention channels; examine what attributes are most attention-compelling; determine how much information can be attended to at any one time, and so on. Similarly, this technique can be applied to musical sequences. The subject can be presented with two simultaneous sequences of notes one to each ear, and the resultant percept examined in various ways.

The technique was used in a recent set of experiments, employing computer-controlled sine-wave tones of equal amplitude, and with simultaneous onsets and offsets. Subjects were presented with dichotic tonal sequences, and asked to report what they heard. The results were quite surprising, and demonstrate the operation of two different channelling principles for musical sequences.

Spatial location

The tonal pattern first employed is shown in Figure 13(a) (Deutsch, 1974b, 1974c). It can be seen that this consisted of a sequence of notes which alternated in pitch from one octave to another. The same sequence was presented simultaneously to both ears; however, when one ear received the high note the other ear received the low note and vice versa. This pattern was continuously presented without pause for 20 seconds; and listeners heard the sequence with earphones placed first one way and then the other.

Surprisingly, none of the 86 subjects employed in this experiment was able to guess what this simple stimulus was. Further, people differed radically in the way the sequence was perceived. The majority of listeners

(a) STIMULUS

(b) PERCEPT

Figure 13 (a) Representation of the dichotic tonal sequence producing the octave illusion. (b) Representation of the illusory percept most commonly obtained. (From Deutsch, 1974c.)

obtained the illusory percept which is displayed in Figure 13 (b). It can be seen that this consisted of a single note the apparent location of which shifted back and forth from ear to ear; and the apparent pitch simultaneously shifted back and forth from one octave to the other. Again, for most of these subjects, when the earphones were placed in reverse position the apparent locations of the high and low notes remained fixed. This created the illusion that the earphone which had been emitting the high notes was now emitting the low notes, and vice versa.

On analysis, it was found that the handedness of the subjects differed statistically in terms of the localization patterns for the two notes at the two ears. Right-handers tended strongly to hear the high notes on the right and the low notes on the left, but left-handers showed no such tendency. This pattern of results indicates that listeners tend to localize the high notes to the dominant side and the low notes to the nondominant.

In considering the possible foundations for this illusion, it was hypothesized that it was based on the operation of two independent decision mechanisms: the first mechanism determines what pitch we hear, and the second determines where the note appears to be coming from. More specifically, it was assumed that when presented with this dichotic sequence the listener attends to the sequence of pitches arriving at one ear and suppresses the other – more often the sequence arriving at the dominant ear is attended to rather than the nondominant. It was further assumed that the listener localizes each note at the ear receiving the higher frequency, regardless of which frequency is in fact perceived. The combined operation of two such decision mechanisms would give rise to the percept of a single note which alternated simultaneously in both pitch and localization, this percept being independent of the position of the earphone.

In order to test this hypothesis, a new dichotic sequence was devised (Deutsch and Roll, 1976). This sequence consisted of three high notes followed by two low notes on one channel, and simultaneously three low notes followed by two high notes on the other. This pattern was repetitively presented ten times without pause, and listeners were asked to report what they had heard. The position of the earphones was then reversed and the procedure repeated.

Only right-handers were employed in this experiment. It was found that most of the subjects reported sequences consisting of one note at a time; and in confirmation of the hypothesis, each note appeared to be localized at the ear which received the higher frequency. Furthermore, on any given stimulus-presentation, most subjects reported three high notes followed by two low notes, or two high notes followed by three low notes. They thus reported the pitch information delivered to one ear and ignored the other. And, also in confirmation of the hypothesis, there was a significant tendency to follow the pattern of pitches delivered to the right ear rather than to the left, for both earphone positions.

In further experiments the stimuli were presented through loudspeakers rather than earphones. Analogous effects were obtained, which shows that in perceiving such sequences the listener attends to the pitch information which emanates from one location in auditory space and "suppresses" the other. Furthermore, there is a tendency in right-handers to attend to the pitch information emanating from the dominant, rather than the nondominant, side of auditory space (Deutsch, 1975d).

Frequency range

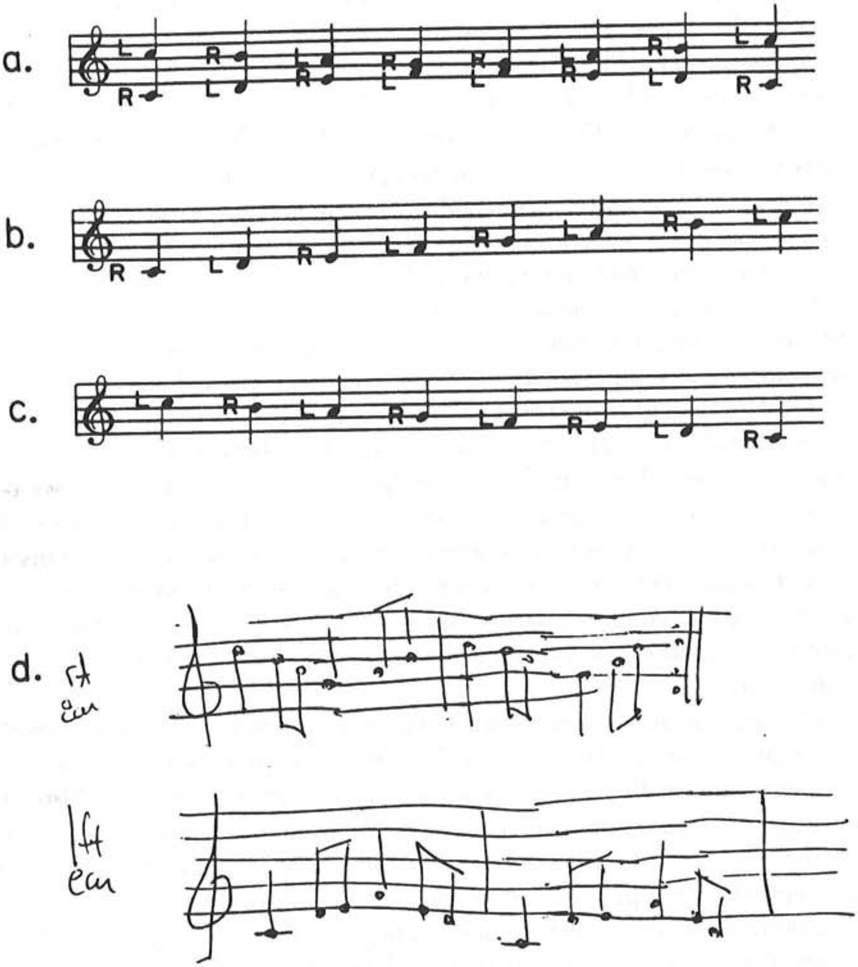
The experiments so far reported involved a sequence of two alternating pitches. In a further experiment, a major scale was used instead as the basic stimulus pattern (Deutsch, 1974d, 1975c). As shown in Figure 14, this scale was presented simultaneously in both ascending and descending form; and switching from ear to ear so that when a component of the ascending scale was in one ear a component of the descending scale was in the other, and vice versa. This pattern was repeated ten times without pause, and subjects listened to the sequence with earphones placed first one way and then the other.

This sequence also produced a variety of perceptual illusions. Most commonly, subjects reported hearing two melodic lines; a higher one and a lower one, that moved in contrary motion. Moreover, the higher tones all appeared to be emanating from one earphone and the lower tones from the other. Right-handers (but not left-handers) tended significantly to hear the higher notes on the right and the lower notes on the left. Indeed, about half of the right-handers tested reported this pattern of localization with the earphones positioned both ways. Thus when the earphone positions were switched around, it appeared to these subjects that the earphone that had been emitting the higher notes was now emitting the lower notes and vice versa. Figure 14(d) illustrates this phenomenon. This reproduces the written report of a subject with absolute pitch. His written statement "reverse headphones/same result (high in rt. ear)" shows that the higher notes were localized in the right ear and the lower notes in the left, regardless of the positioning of the earphones.

A different result was obtained by other subjects. These perceived only a single stream of four notes, which repetitively descended and then ascended. They perceived little or nothing of the other stream. All these subjects, when asked to shadow the sequence by singing, shadowed the upper stream and not the lower one.

This sequence therefore demonstrates a different channelling principle in music. Here all listeners formed perceptual channels based on frequency range. They either heard only the higher notes and ignored the lower, or they heard the higher and lower notes as two simultaneous but separate musical channels. There was in addition a significant tendency among right-handers to refer the higher stream to the dominant side of auditory space, and the lower stream to the nondominant.

This principle of channelling information by frequency range has also been investigated using rapid sequences of single notes. Miller and Heise (1950) presented listeners with a sequence of two notes alternating at a rate of 10 per second, and found that if the frequencies of these notes differed by less than 15 per cent. the sequence was heard as a trill (i.e. as a single string of related notes). However, as the disparity in frequency between the notes



reverse headphones,
Same result (high in rt ear.)

Figure 14 (a) Representation of the dichotic sequence producing the scales illusion. (b) The ascending component separately; (c) The descending component separately; (d) Illusory percept depicted by a subject with absolute pitch. This type of percept was most commonly obtained. (From Deutsch, D., 1975c, by permission of the *Journal of the Acoustical Society of America,* **59**, 1156–1160. Copyright 1975 by the Acoustical Society of America.)

increased, the sequence was heard instead as two interrupted and unrelated notes. This phenomenon has been termed "fission" by several investigators. Heise and Miller (1951) extended these findings to patterns of several notes, and found that if one of the notes in a rapid repetitive sequence differed sufficiently in frequency from the rest it was heard as isolated from the others – indeed, as appearing to emanate from a separate sound-source. Schouten (1962) also investigated this phenomenon, and found that as the separation between the frequency of successive notes is increased, a reduction in tempo is necessary in order to maintain temporal coherence between successive notes. Van Noorden (1975) made a systematic investigation into the relationship between frequency separation and tempo on the perception of temporal coherence. Subjects listened to melodic sequences and were required either to try to hear temporal coherence or to hear fission. It was found that when subjects were trying to hear coherence, decreasing the tempo from 50 to 150 m sec per note increased the frequency separation within which coherence can be heard from 4 to 13 semitones. However, when the subject was trying to hear fission, decreasing the tempo had little effect on performance. Between these two boundaries there existed a large region in which the listener could direct his attention at will, hearing either fission or temporal coherence.

The separation of tonal sequences by frequency range is extremely common in music. When a single instrument plays a melody and an accompaniment their pitch ranges are generally separate. Also, in contrapuntal music, each voice tends to be confined to a given pitch range. Composers of the early 18th century cleverly took advantage of this perceptual principle by their technique of pseudo-polyphony, or compound melodic line. Their compositions often included rapid sequences of single notes which were drawn from different pitch ranges, with the result that the listener hears two simultaneous melodies (Figure 15).

Dowling (1973) has demonstrated the importance of this principle of frequency separation by showing that when the notes of two well-known melodies are played alternately in rapid succession (at a rate of 8 per second) recognition of the individual melodies is very difficult if their pitch ranges overlap. As one of the melodies is gradually transposed, so that their pitch ranges diverge, recognition becomes increasingly easier. Correct identification is achieved at a frequency separation which leaves the range of the melodies not quite overlapping.

A further interesting property of rapid sequences of notes which are drawn from different frequency ranges was demonstrated by Bregman and

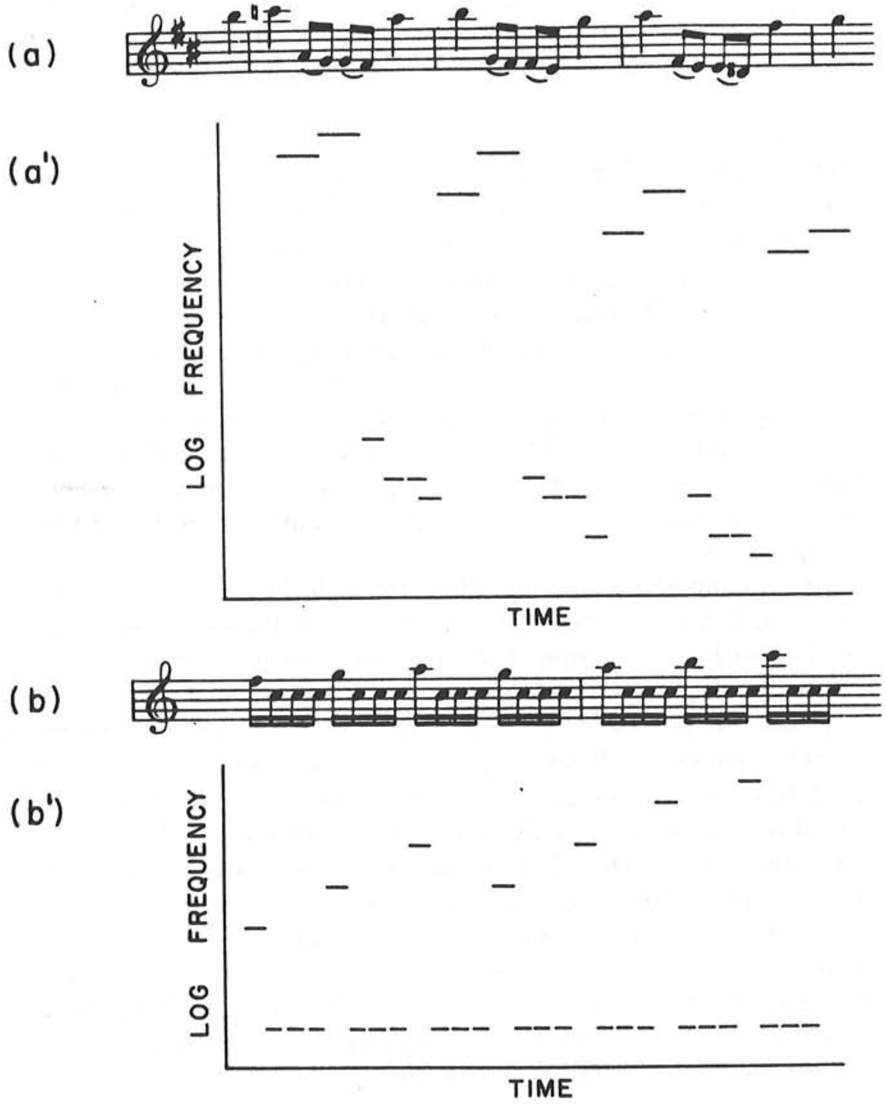


Figure 15 The grouping of melodic stimuli on the basis of frequency proximity. (a) and (b) display the sequences in musical notation; and (a′) and (b′) in plots of log frequency versus time. In sequence (a) we hear two parallel melodies, each in a different frequency range. In sequence (b) a single pitch is repeatedly presented in the lower range; and this provides a ground against which the figure in the upper range is heard. ((a) from Telemann, G. P., *Capriccio for Recorder and Basso Continuo*; (b) from Telemann, G. P., *Sonata in C Major for Recorder and Basso Continuo*.) (From Deutsch, 1975d, by permission of *Scientific American*, 1975, **233**(4), 92–104, Copyright 1975 by Scientific American, Inc.)

Campbell (1971). They found that it was easy to perceive the order of notes in a given frequency range; however, such perception was extremely difficult for notes drawn from different ranges.

Timbre

What happens when differences in timbre are introduced between successive notes? In much orchestral music, especially of the late eighteenth century, timbre is often used as a marker of sequential groupings; that is, adjacent phrases are played by different instruments. Further, in music for more than one instrument, such as duets, overlaps in pitch range commonly occur, and we have no difficulty in separating the different voices. This would imply that a sequence of notes of different timbres would not be heard as coherent, but one would hear fission instead. Indeed, Warren et al. (1969) and Warren and Obusek (1972) have shown that listeners find it very difficult to identify the order of elements in repetitive sequences of three or four unrelated sounds (hisses, buzzes and tones) played at a rate of five per second.

An experiment by Van Noorden (1975) shed interesting light on this question. It has long been known that a complex tone consisting of a number of harmonic components has a pitch which corresponds to the frequency of the fundamental, even when the fundamental is not present (Schouten, 1940). Van Noorden exploited this phenomenon to investigate whether temporal coherence between successive notes depends on their pitch similarity or on similarity between their frequency components. He found that, both when a pure tone alternated with a complex tone of the same pitch but which lacked the fundamental frequency, and also when two complex tones alternated which had the same pitch but whose frequencies lay in frequency ranges which did not overlap, fission was heard. However, if the two complex tones contained similar frequency components, temporal coherence was heard instead. Van Noorden therefore concluded that temporal coherence depended on contiguity between the underlying frequency components of the elements of the sequence, rather than on their perceived pitch.

Other principles

This review has focussed primarily on two channelling principles in music: chanelling based on spatial location and channelling based on frequency. There are without doubt many other principles. One that was mentioned briefly is loudness. Egan et al. (1954) have demonstrated that two simultaneous verbal messages interfere with each other less when these are presented at different loudness levels. Further, Dowling (1973) found that it was easier to separate interleaved melodies when these differed in loudness. We might also expect to find channelling based on other organizing principles of perception, for instance the Law of Good Continuation. Further, it is possible that familiar sequences, such as well-known melodies, might be treated as separate channels. However, these suggestions are at present no more than speculative.

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