THE ORGANIZATION OF SHORT-TERM MEMORY FOR A SINGLE ACOUSTIC ATTRIBUTE

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I. INTRODUCTION

In the formation of human memory models, the characteristics of nonverbal information storage have received very little attention. This may be attributed largely to the popularity of the three-stage view of memory as a framework for such models. This view holds that nonverbal information is retained in highly transitory and nonspecific fashion, and that it can be saved from obliteration only by a process of verbal labeling that enables it to enter a linguistic short-term memory store. If the nonverbal store were indeed simply an unstructured buffer that retains information before verbal encoding, the study of its characteristics would clearly be of little general interest. There is growing evidence, however, that this view is incorrect. This chapter reviews such evidence with regard to the duration of the nonverbal memory trace, and then describes a series of experiments exploring the behavior of one specific nonverbal memory system over time periods characteristic of short-term memory. These experiments demonstrate that with the use of simple stimulus materials, which may be precisely and systematically varied, the short-term storage of nonverbal information can be shown to possess a systematization and specificity rivaling any found in verbal memory studies.

II. DURATION OF NONVERBAL MEMORY TRACES

The majority of experiments on the duration of sensory memory have been concerned with visual storage. Here, attention has focused particularly on Sperling's (1963, 1967) model. Sperling hypothesized that visual information first enters a large-capacity visual information store (VIS) where it decays very rapidly, within a second. The information is saved from obliteration by its serial transfer into an auditory short-term store (AIS) of strictly limited capacity, where it is retained through a process of linguistic rehearsal. If visual information survives in memory only by being recoded and retained in a limited-capacity acoustic store, then the amount of information retained in this store should be constant independent of its sensory mode. Various studies involving combined presentation of visual and acoustic materials show that this is not the case (Sanders & Schroots, 1969; Scarborough, 1972a; Henderson, 1972). We can recall substantially more information if some of it visual and some of it acoustic than if only one stimulus modality is involved.

Other inconsistencies with Sperling's theory are revealed by studies demonstrating the persistence of a visual trace after several seconds filled with auditory-linguistic activity. Parks, Kroll, Salzberg, and Parkinson (1972) required subjects to compare two visually presented letters when these were separated by an 8-sec retention interval filled with auditory shadowing. They found that subjects responded faster to a physically identical match rather than to a name match, even given this delay. Further, Kroll, Parks, Parkinson, Bieber, and Johnson (1972) presented test letters either visually or acoustically and required subjects to recall them after periods of auditory shadowing. The letters were recalled better when they had been presented visually rather than acoustically even after a delay as long as 25 sec (see Chapter VI of this volume for a detailed discussion of these experiments). Scarborough (1972b), using the Peterson technique, found similarly that trigrams were better retained after 18 sec of backward counting when they had been presented visually rather than acoustically.

Experiments on recognition of pictures have demonstrated the persistence of visual traces for even longer periods of time. Such recognition has been shown to be remarkably accurate, even when hundreds of pictures are compared (Nickerson, 1965; Shepard, 1967). In these experiments a delay of many minutes intervened between the initial presentation of a picture and its second presentation in a recognition test. The involvement here of a visual rather than a verbal store is shown by Shepard's finding that recognition of pictures was substantially better than recognition of words or sentences. Shepard found further that even after a delay of a week, memory for pictures was nearly equivalent to memory for verbal materials when the test immediately followed stimulus presentation. Further evidence for the remarkably strong persistence of visual memory comes from a study by Bahrick and Boucher (1968), who concluded that verbal recall of pictures presented after two weeks depended largely on retrieval from visual storage.

Other investigations into the duration of nonverbal memory have been concerned with the acoustic properties of speech. On the basis of a series of experiments on the suffix effect, Crowder and Morton have proposed that auditory information is retained in a "precategorical acoustic store," where it decays within a second or two, and is also subject to displacement by subsequent acoustic events (Crowder & Morton, 1969; Morton, 1970). However, other studies have demonstrated that we can retain the sensory attributes of speech sounds for longer periods. Cole (1973) required subjects to decide whether two spoken letters were the same or different when they were presented either in the same voice or in different voices. He found that even with a retention interval of 8 sec, the subjects took a shorter time to respond "same" when the letters were spoken in the same voice rather than in a different voice. The subjects must therefore have been storing the acoustic attributes of the spoken letters during this period. Murdock and Walker (1969), on the basis of experiments comparing free recall of words presented either acoustically or visually, also concluded that prelinguistic auditory information was retained in memory for at least 5 to 10 sec.

Further convincing evidence that we can retain the acoustic properties of speech sounds for relatively long periods has been provided by Pollack (1959). He presented subjects first with a test word embedded in noise, and later with a list of words that included the test word. Subjects were required to choose which of the words in the list was the test word. When the number of words in the list was reduced, the subjects showed improved recognition of the test word, and this improvement was manifest even after a 15-sec delay between presentation of the test word and the list of alternatives. The subjects must therefore have been storing some acoustic representation of the test word during the delay. Crossman (1958) obtained a similar finding. He played a test word at half-speed on a tape recorder, and after a delay presented subjects with a list of words containing the original word. Subjects were able to improve their recognition of the test word when the number of words in the list was reduced, even after a 40-sec delay between presentation of the test word and the list of alternatives. Indeed, considering the ease and speed with which we recognize a familiar voice by its intonation, we must be capable of storing the acoustical properties of speech sounds on a very long-term basis.

These studies demonstrate that we can store nonverbal stimulus attributes over substantially longer time periods than those predicted by the three-stage model. It must be concluded that the sensory attributes of a stimulus survive in memory after verbal encoding, and that they continue to be retained in parallel with the verbal attributes. This view has been argued persuasively by Posner in a series of articles (Posner, 1967; Posner, 1972; Posner & Warren, 1972). Posner assumes further that nonverbal attributes compete with verbal attributes for processing capacity in a limited capacity system. This theory is discussed later for the specific case of pitch memory.

Finally, it must also be stressed that there is a basic implausibility about the view that nonverbal memory is only transient. Shepard (1967) and Paivio (1969) have argued persuasively for the role of mental images as precursors of verbal recall. Unfortunately, in the case of memories for which verbal descriptions are possible, one can always argue—even though implausibly—that the basic mode of such information storage is really verbal. There is one incontrovertible example, however, of an enduring nonverbal memory system; this is the system responsible for storing musical information. Although we commonly recognize melodies and long works of music by name and can, with musical training, label abstracted tonal relationships, the basic process of music recognition cannot conceivably be verbally mediated. We constantly recognize melodies as familiar without having learned their names. Further, we can accurately identify very short sequences taken from the middle of long works of music. It is also striking how acutely aware we may be of a single error or distortion in the performance of a musical composition. It is clear from such considerations that musical information must be stored in highly specific form for substantial periods of time.

III. PROPOSED MODELS OF NONVERBAL MEMORY ORGANIZATION CONSIDERED FOR THE CASE OF TONAL PITCH

There are various theories concerning the nature of nonverbal memory. Broadbent (1958, 1963) has proposed that nonverbal information simple decays with time: “The stored information decays very rapidly as a function of time, and not as a function of intervening activity” (Broadbent, 1963). An alternative suggestion was made by Posner (1967), who theorized that the maintenance of precategorical information in memory requires the use of a portion of a limited capacity system: “…in verbal terms it may be involve covert speech, while in other situations…something more akin to concentration may be appropriate” (Posner, 1967). Concerning acoustic information, Crowder and Morton (1969) have hypothesized the existence of a precategorical acoustic store where information is subject both to decay and also to displacement by subsequent acoustic events.

Concerning Broadbent’s decay theory, it has indeed been found that memory for tonal pitch deteriorates with time in the absence of intervening stimulation (Koester, 1945; Harris, 1952; Bachem, 1954). However, the rate of decay is much slower than Broadbent supposed. Harris (1952) found that with a retention interval of 15 seconds, the difference threshold for pitch was elevated only by .8 cps or by 3.7 cps, depending on whether the standard stimulus was fixed during the experimental session or whether it varied. Further, Broadbent was incorrect in assuming that the presence of other stimuli during the retention interval would not affect the degree of memory loss. Several studies have shown that the interpolation of a tone during the retention interval between a standard and a comparison tone produces further memory deterioration (Wickelgren, 1966, 1969; Elliot, 1970). Increasing the number of interpolated tones, when the retention interval is held constant, results in increased memory loss (Rimm, 1967; Deutsch, 1970a; Massaro, 1970).

What is the basis for the memory interference produced by interpolated tones? The hypotheses of Posner (1967) and of Crowder and Morton (1969) give rise to testable predictions.

If information concerning tonal pitch is held in a short-term memory store of limited channel capacity, then the larger the number of bits of information processed during the retention interval, the greater should be the resultant memory decrement. Alternatively, if this information is held in a precategorical acoustic store that is limited to a certain number of items, then the amount of memory decrement should depend on the number of acoustic items interpolated during the retention interval. Such acoustic items include spoken digits, since these were the stimuli employed by Crowder and Morton (1969) in their experiment on the retention of precategorical acoustic information.

I tested these predictions in two experiments. Basically, I compared the effects on memory of interpolating two different types of information during the interval between a standard and a comparison tone. The first type of interpolated information consisted of other tones, and the second type consisted of spoken numbers of equal loudness to the tones. The number of items in each interpolated sequence remained constant throughout the experiment. Further, the numbers and tones were both chosen from the same size ensemble and so carried the same number of bits of information. Theories of memory loss based on the concept of a limited capacity storage system, either general or precategorical acoustic in nature, would predict the intervening number sequences to cause at least as much disruption in pitch recognition as the intervening tonal sequences. However, if information concerning tonal pitch were stored in a specialized system, the intervening number sequences would not necessarily cause memory disruption equivalent to the disruption caused by intervening tones.

The first experiment consisted of two conditions. In the first condition, pitch recognition was required after a 6-sec interval during which 8 extra tones were played. The second condition was identical to the first, except that instead of tones, 8 spoken numbers were interpolated. The numbers were of equal loudness to the tones and were spaced identically and selected randomly from the same size ensemble. In both conditions, subjects were required to listen to the standard tone, ignore the 8 interpolated items, listen to the comparison tone, and then judge whether the standard and comparison tones were the same or different in pitch. When the interpolated items were further tones, the error rate was very high (40.3%). However, when the interpolated items were spoken numbers, the error rate was close to zero (2.4%).

It would appear from this experiment that memory for tonal pitch is subject to a large interference effect caused specifically by other tones and not due to some general storage limitation. It could, however, be argued that although the subjects were instructed in both conditions to ignore the intervening items, they achieved this much more effectively when these were numbers than when they were tones. The results might therefore be explained in terms of an involuntary selective attention mechanism, which allowed the intervening numbers to be ignored but which compelled attention to the intervening tones. I therefore performed a further experiment, in which recall of the intervening numbers was also required. This insured that the numbers were in fact attended to and stored in memory.

There were four conditions in this second experiment (Deutsch, 1970b). In all conditions, subjects listened to a standard tone that was followed 5 sec later by a comparison tone, and they judged whether the two were the same or different in pitch. In Condition 1, six extra tones were played during the retention interval. In Conditions 2, 3, and 4, six spoken numbers were incorporated instead. These were of equal loudness to the tones and were spaced identically. In Condition 1, subjects were instructed to ignore the intervening tones and indicate whether the standard and comparison tones were the same or different in pitch by writing “S” or “D.” In Condition 2, they were similarly instructed to ignore the numbers and compare the pitch of the standard and comparison tones. In Condition 3, in addition to comparing the tones, subjects were required to recall the 6 numbers in their correct order. Having heard the entire sequence they wrote "S" or "D, " followed by the numbers. In Condition 4, the pitch of the standard and comparison tones was always the same, and the subjects were informed of this. They were instructed to listen to the total sequence and then to write "S" followed by the numbers in their correct order. Condition D therefore provided a baseline estimate for number recall in the absence of a tonal memory load.

The results of this experiment are shown on Table 5-1. It can be seen that here again, the intervening tones caused considerable memory disruption. However, when numbers were instead interpolated, the error rate was minimal even when recall of these numbers was required. Further, the requirement to remember the standard tone produced no decrement in number recall. The memory disruption produced by interpolated tones could not therefore have been due to general factors, such as prevention of rehearsal, limitation in information-storage capacity, or displacement in a general, precategorical acoustic store of limited capacity. One must conclude that a specialized system exists for the storage of tonal pitch.

The memory dissociation described here is subjectively very compelling; many of the subjects expressed surprise at the lack of strain imposed by the two simultaneous memory tasks. It might be tempting to explain such a striking dissociation in terms of gross anatomical differences in the processing of verbal and musical information. Dichotic listening experiments have shown that right-handed subjects identify verbal stimuli more accurately when these are presented to the right ear rather than to the left (Kimura, 1961; Bryden, 1963; Dirks, 1964). The reverse happens when certain nonverbal materials are dichotically presented. This has been found, for instance, with hummed melodies (King and Kimura, 1972), melodies played on woodwinds and strings (Kimura, 1964), and environmental sounds (Curry, 1967; Knox and Kimura, 1970). One might, therefore, suggest that speech sounds are stored in the dominant hemisphere, tones in the nondominant, and that the present dissociation is due to a lack of interference between the hemispheres. However, recent dichotic listening experiments show the situation to be more complicated. Studdert-Kennedy and Shankweiler (1970) present evidence that the auditory parameters of speech are processed in both hemispheres, with the dominant hemisphere providing further extraction of linguistic features. Further, although consonants are better identified when presented to the right ear, vowels appear either to be better identified when presented to the left ear, or to be equally well processed through either ear (Shankweiler & Studdert-Kennedy, 1967; Kimura, 1967; Shankweiler & Studdert-Kennedy, 1970). Given this evidence, and if we accept the argu-

TABLE 5-1*

	Task	
Condition	**Pitch Recognition (%)**	**No. Recall (%)**
1. Pitch recognition with intervening tones 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

*Percent errors in pitch comparison as a function of type of information interpolated during the retention interval. Number recall was judged correct on any trial only if all the numbers were correctly recalled in order. The error rate in Condition 1 was significantly greater than in either Conditions 2 or 3 ($p < .001$ for both comparisons on sign tests). From Deutsch, D., 1970, by permission of *Science*, **168,** 1604-5. Copyright 1970 by the American Association for the Advancement of Science.

ment that asymmetries in dichotic listening are due to differential processing by the two hemispheres, it appears that both hemispheres in the present experiment would be involved in processing the numbers. Indeed, Crowder (1971) has shown that the properties, which had originally been found to characterize the precategorical acoustic storage of verbal materials, are exhibited by vowels but not by consonants. On this basis, together with the evidence from laterality studies, he proposes that the precategorical acoustic store for verbal materials is a property of the nondominant rather than the dominant hemisphere.

Further, the studies quoted above, which demonstrate a left ear advantage for perception of dichotically presented musical materials, both involved the simultaneous variation of several acoustic attributes, and so cannot be used to draw inferences about the processing of pitch information *per se*. Studies addressed to the processing of more specific musical attributes have produced a rather complicated picture. For instance, Gordon (1970) obtained a significant left ear advantage for dichotically presented chords, but not for melodies. Spellacy (1970) found a significant left ear superiority for perception of dichotically presented violin melodies, but not for timbre, temporal patterns, or patterns of tones varying in frequency alone. Doehring (1972) obtained a significant left ear advantage for monaural intensity discrimination, but not for frequency discrimination.

It would appear from such findings that musical information is indeed processed asymmetrically by the auditory pathways, but that this asymmetry cannot be defined in terms of a simple "if nonverbal, then nondominant" rule. I have investigated this question further as applied to the processing of pitch information, and have come across some very surprising illusions, which add further complexity to the situation.

In my first experiment I presented subjects with the stimulus pattern shown in Figs. 5-1a and 2a (Deutsch, 1974b&c). It can be seen that this consisted of a sequence of 250 msec tones. Each tone was either 400 Hz or 800 Hz, and these frequencies were presented in strict alternation.

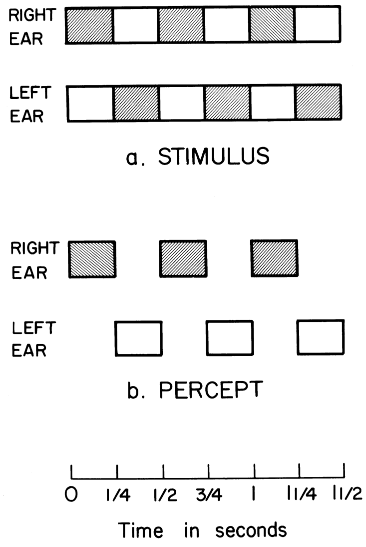
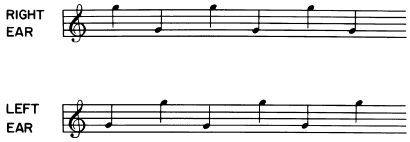
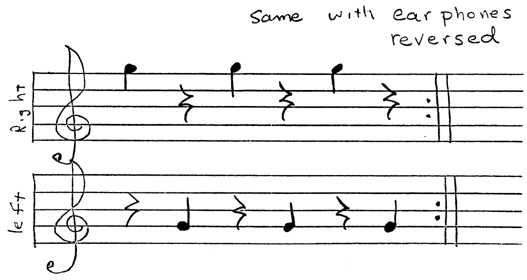


Fig. 5-1 Diagrammatic representation of the first dichotic sequence, and the illusory percept most commonly obtained. Filled boxes represent tones of 800 Hz, and unfilled boxes tones of 400 Hz. From Deutsch, D., 1974, by permission of *Nature*, 251, 307-309. Copyright 1974 by Macmillian Journals, Ltd.



a. STIMULUS



b. PERCEPT

Fig. 5-2 Representation in musical notation of the first dichotic sequence, and the percept depicted by a right-handed subject with absolute pitch. $G_4 = 392\ Hz$, and $G_5 = 784\ Hz$; these are closest in the musical scale to the 400 *Hz* and 800 *Hz* presented. The subject's own written statement: "Same with earphones reversed" shows that the same asymmetrical percept was obtained regardless of the positioning of the earphones. Fig. 5-2 (b) from Deutsch, D., 1974, by permission of *Nature*, 251, 307-309. Copyright 1974 by Macmillian Journals, Ltd.

The identical sequence was presented to both ears simultaneously at equal amplitude, except that when one ear received 400 Hz the other ear received 800 Hz, and vice versa. This sequence of alternating tones was presented without pause for 20 sec. The tones were sinusoids, and their phase relationship varied randomly.

Amazingly, this simple dichotic sequence was almost never perceived correctly. Out of well over a hundred listeners, only one reported the correct percept, and this listener had strabismus and other signs of neurological abnormality (which may be coincidental, but may also provide a clue to the neurological basis for the illusory percepts). The illusion most commonly obtained is diagramed in Fig. 5-1b. It can be seen that a single tone was perceived, which oscillated from one ear to the other, and whose pitch also oscillated from one octave to the other in synchrony with the localisation shift. This percept is also illustrated in Fig. 5-2b, which reproduces the written report in musical notation of a subject with absolute pitch.

There is clearly no simple way to explain this illusory percept. We can account for the perception of a single tone oscillating from ear to ear by assuming that the listener alternately processes the information from one ear and suppresses the other. But then the pitch of this alternating tone should not shift with a shift in its apparent localisation. We can also account for the perception of a single tone oscillating from one octave to the other by assuming that the listener consistently follows one ear alone; but then the tone should not appear to oscillate from ear to ear. The illusion of a single tone which oscillates simultaneously both in pitch and in localisation appears quite paradoxical.

This illusion has a further surprising aspect: right-handers and left-handers exhibit different patterns of localisation for the two pitches at the two ears. These are shown in Table 5-2. Each subject was presented with the sequence twice for 20 sec each time, with earphones placed first one way and then the other. The order of earphone placement was strictly counterbalanced for

TABLE 5-2*

	RR	LL	Both
Right-Handers	25	5	1
Left-Handers	6	7	4

*Patterns of apparent localization for the two pitches at the two ears in subjects who perceived a single tone oscillating from one octave to the other. Figures show the number of right- or left-handed subjects obtaining a given localization pattern.
RR: High tone localized in the right ear and low tone in the left on both stimulus presentations.
LL: High tone localized in the left ear and low tone in the right on both stimulus presentations.
Both: High tone localized in the right ear and low tone in the left on one presentation; high tone localized in the left ear and low tone in the right on the other. From Deutsch, D., 1974, by permission of *Nature*, 251, 307-309. Copyright 1974 by Macmillian Journals, Ltd.

both right and left-handed subjects. It can be seen that right-handers tended significantly to maintain a given localisation pattern when the placement of the earphones was reversed, and also to hear the high tone in the right ear and the low tone in the left ($p < .001$, two-tailed, on binomial tests in both instances). (The percept reproduced in Fig. 5-2b is that of a typical right-hander.) On the other hand, the left-handers as a group did not preferentially localise the tones either way, and showed only a marginally significant tendency to maintain a given localisation pattern when the earphones were placed in reverse position ($p = .05$, two-tailed, on a binomial test). When these results are related to other findings on patterns of hemispheric dominance and handedness (Hécaen and de Ajuriaguerra, 1964; Brain, 1965), they suggest strongly that we tend to localise high tones to our dominant side and low tones to our nondominant side.

A further experiment demonstrated that these localisation patterns are based on the pitch relationships between the competing tones, and not on a pattern of ear preference at different pitch levels. Twelve subjects who had consistently localised the 800 Hz tone in the right ear and the 400 Hz tone in the left were presented with sequences alternating between 200 Hz and 400 Hz, 400 Hz and 800 Hz, and 800 Hz and 1600 Hz in the counterbalanced order. With the exception of one report on one sequence, the higher of each pair of tones was always localised in the right ear and the lower in the left. (Thus, for instance, the 800 Hz tone was localised in the right ear when it alternated with the 400 Hz tone, but in the left ear when it alternated with the 1600 Hz tone).

The percept of a single tone oscillating synchronously both in pitch and in localisation was reported by 58% of the right-handers and 52% of the left-handers formally tested. Another 25% of the right-handers and 9% of the left-handers reported, instead, a single tone oscillating from ear to ear, whose pitch either remained constant or changed only slightly as its localisation shifted. In matching experiments the pitch of this oscillating tone was found by some subjects to be closest to that of the 800 Hz tone, and by others to be closest to the 400 Hz tone. The remaining 17% of the right-handers and 39% of the left-handers reported a variety of complex percepts, such as two alternating pitches localised in one ear, and a third pitch appearing intermittently in the other (either synchronized with one of the alternating tones, or out of synchrony with either). A significant difference was found between right- and left-handers in terms of the proportions obtaining these different categories of percept. ($\chi^2 = 6.8$, df = 2, $p < .05$.)

We may now ask which ear is followed when the subject perceives a single tone oscillating from one octave to the other. This percept is consistent with following the sequence of pitches presented either to the right ear or to the left, since this same tonal pattern is presented to both

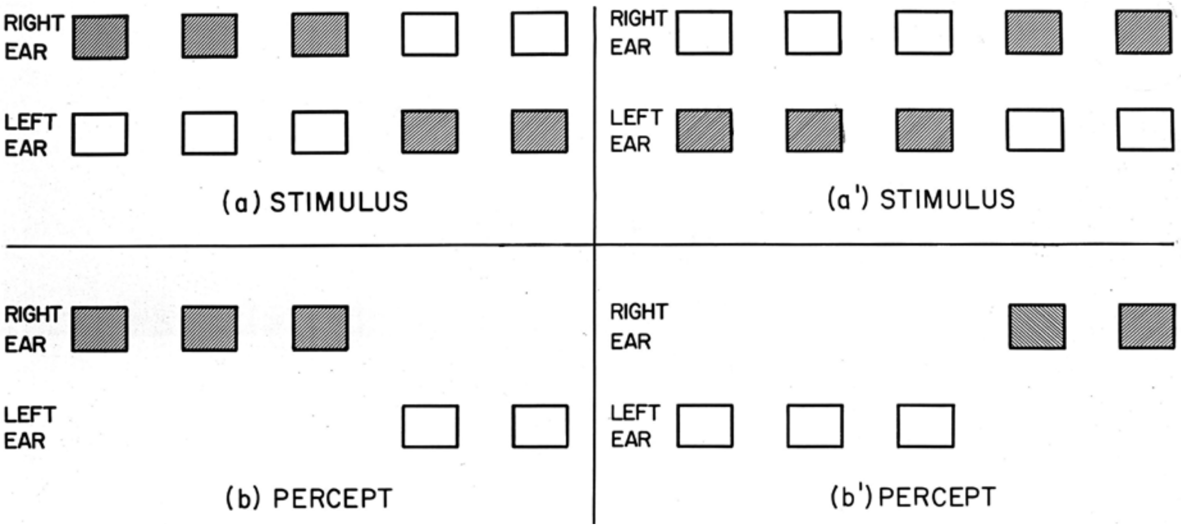


Fig. 5-3 Diagrammatic representation of the second dichotic sequence, and the illusory percept most commonly obtained. Filled boxes represent tones of 800 *Hz* and unfilled boxes of 400 *Hz*. (a) Stimulus pattern with channel A to the right ear and channel B to the left ear. (b) Illusory percept with earphones positioned as in a. (a′) Stimulus pattern with channel B to the right ear and channel A to the left ear. (b′) Illusory percept with earphones positioned as in a′.

ears. A new dichotic sequence was, therefore, constructed in which each ear received a different pattern of pitches. As shown in Figs. 5-3a and 3á, this sequence consisted of three high (800 Hz) tones followed by two low (400 Hz) tones on one channel, and simultaneously three low (400 Hz) tones followed by two high (800 Hz) tones on the other. This pattern was repeated ten times without pause, and each subject listened to the sequence with earphones placed first one way and then the other. (The order of earphone placement was strictly counterbalanced across subjects.)

The results were again surprising. Contrary to expectations from the previous literature, right-handed subjects tended significantly to report the pattern of pitches fed to the *right* ear rather than to the left. (Thus, with channel A to the right ear and channel B to the left, they tended to report three high tones followed by two low tones; with channel B to the right ear and channel A to the left, they tended to report three low tones followed by two high tones.) No significant ear preference was demonstrated among left-handers. However, lateralisation of the tones followed a different rule. All subjects lateralised each tone to the ear that received the higher of the two frequencies, regardless of which ear they followed for pitch and regardless of whether the tone was heard as high or low. This combination of two independent rules produced a most paradoxical percept, which is illustrated in Figs. 3b and 3b´ for the case of listeners who followed the right ear for pitch. With channel A to the right ear and channel B to the left, these listeners perceived a repetitive presentation of three high tones to the right followed by two low tones to the left. With earphone positions reversed, the same segment of tape was now heard as a repetitive presentation of two high tones to the right followed by three low tones to the left! Clearly this is an impossible auditory object!

So far, the following of pitch information fed to one ear rather than the other suggests a simple inhibitory interaction between pathways from the two ears in determining pitch (but not lateralisation). However, in a further experiment, I presented the sequence shown in Fig. 5-1a channeled through two spatially separated loudspeakers rather than through earphones. To my surprise the illusion was still obtained, even though both sequences were now presented to both ears with only localisation cues to distinguish them. When the listener was positioned equidistant between the two speakers, oriented so that one speaker was exactly on his right and the other exactly on his left, the high tones were heard as coming from the speaker on the right and the low tones from the speaker on the left. When the listener rotated slowly, the tones appeared to move with him (although the speakers were stationary) so that the high tones remained on his right and low tones on his left. When he stood facing one speaker, with the other speaker behind him, the illusion abruptly disappeared, and a single tone was heard as coming from both speakers simultaneously (as though they had been passed through a mixer). But as the listener continued turning the illusion abruptly reappeared, with the high tones still on the right and the low tones still on the left. Thus when the listener had turned 180% from his original position, the speaker which had originally appeared to be emitting the high tones now appeared to be emitting the low tones, and the speaker which had originally appeared to be emitting the low tones now appeared to be emitting the high tones! This makes a very dramatic demonstration of the illusion, and shows that it must have a complex basis.

The two-channel listening paradigm was further elaborated using a more complicated tonal sequence. As shown on Fig. 5-4a, this new sequence consisted of the *C* major scale with successive tones alternating from ear to ear. This scale was presented simultaneously in both ascending and descending form, such 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. Figs. 5-4b and 4c show these ascending and descending scales separately; thus the sequence shown in Fig. 5-4a was simply the superposition of the two sequences shown in Figs. 5-4b and 4c. The tones were again sinusoidal, of equal amplitude, and 250 msec in duration; and here there were no gaps between adjacent tones. Each sequence was presented ten times without pause, with earphones positioned first

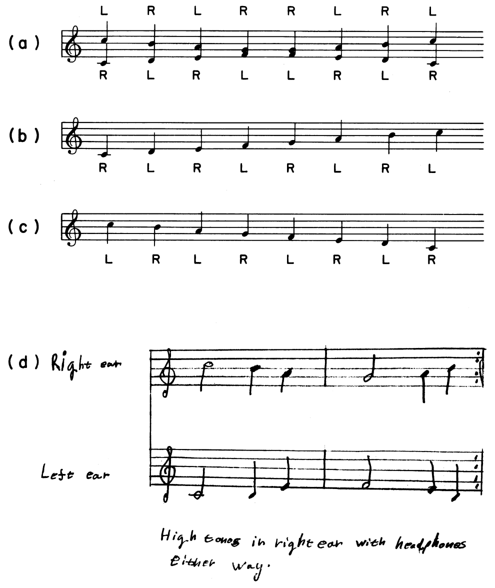


Fig. 5-4 Representation in musical notation of the third dichotic sequence, and the percept depicted by a right-handed subject with absolute pitch. (a) The C major scale, with successive tones alternating from ear to ear, and played simultaneously in both ascending and descending form. (b) The ascending component alone. (c) The descending component alone. (d) Subject's own report of the dichotic sequence. His written statement: "High tones in right ear with headphones either way" shows that the higher tones were localized in the right ear and the lower tones in the left, regardless of earphone placement.

one way and then the other. Subjects reported what they heard verbally and afterwards shadowed the sequences by singing while I monitored the tape on separate earphones (Deutsch, 1974d).

Surprising difficulties were again encountered in perceiving the dichotic sequence, with only one subject out of seventy reporting it correctly. Yet very few subjects misreported the separate ascending or descending sequences, so these difficulties were not due to a simple inability to follow the 250 msec switching rate. Basically, the dichotic sequence was misperceived along two different lines. The majority of subjects reported the correct pattern of pitches, but localised them incorrectly; most commonly, the higher tones were all heard in one ear and the lower tones in the other. Right-handers (but not left-handers) tended significantly to mislocalise the higher tones to the right ear and the lower tones to the left, irrespective of earphone position. This illusory percept is shown in Fig. 5-4d, which reproduces the written report of a right-handed subject with absolute pitch. The remainder of the subjects reported the higher tones, but little or nothing of the lower tones. No subject adopted a different channeling principle, such as reporting the pattern of pitches presented to one ear rather than to the other.

This set of experiments presents a complicated picture of ear advantage in the processing of pitch information. For one type of sequence, tones localised to the dominant side appear to inhibit those localised to the nondominant side in determining pitch (but not lateralisation); for another, the perceived sequence of pitches appears to depend on a principle of channeling that cuts across ear of input. An illusion whereby the higher of two simultaneous tones is mislocalised to the dominant ear, and the lower to the nondominant, adds further complexity to the situation.

Given this ambiguity at the perceptual level, very little can be inferred from dichotic listening studies about the locus of the pitch-memory system. The finding that differences in localisation can produce the same effect as differences in ear of input also raises doubts about the validity of drawing simple inferences about hemispheric specialisation of function from the use of dichotic listening technique. Direct neurological studies are much more convincing, and it is clear from such studies that the nondominant hemisphere is capable of musical information storage (Bogen, 1969). However, it is not clear that memory for pitch *per se* is specifically disrupted by lesions of the nondominant hemisphere; the controlled studies which would answer this question have yet to be performed. At all events, we cannot conclude from the studies reviewed here that the properties of tones and the acoustical properties of words are stored in separate hemispheres. Rather, the evidence points to a specialised system for the retention of pitch information.

IV. ORGANIZATION OF THE PITCH MEMORY SYSTEM

Given the conclusion that tonal information is retained in a specialized system, we can attempt to characterize this system in further detail. An everyday knowledge of music leads to the conclusion that it must contain several subdivisions. For instance, we recognize a transposed melody much more readily than we recognize the key it was played in. Memory for the abstracted relationships between the component tones of the melody must therefore be more enduring than memory for the tones themselves. A similar argument holds for transposition of harmonic sequences. Further, there is considerable evidence that we perceive and remember a tone in terms of its position not only along a “tone-height” continuum, but also within an abstracted octave, or “tone-chroma” continuum. As a related phenomenon, our memory for invertable chords is more enduring than memory for the component tones in the chords. A further complexity exists in the storage of timbre. The experiments of Plomp and his collaborators have shown that the timbral qualities of tones are a function of a highly differentiated multidimensional system (Plomp, 1970).

I do not argue that the different subdivisions of the tonal memory system exist in isolation from each other. The evidence shows that complex and often paradoxical relationships exist, at least at the perceptual level, between our processing of pitch, timbre, chords, and melodies (Erickson, 1975). Rather, I take the view that the properties of various subdivisions of this memory system can be experimentally abstracted, and that relationships between these subdivisions can then be studied in further experiments.

In considering the possible organization of the system that stores the pitch of a single pure tone, a very simple hypothesis presents itself: that *the system that retains this information is organized in many ways along the same principles as the system that receives it*. This hypothesis obviously does not assume an identical organization between sensory and memory systems: their very functions require that they differ in important respects. For instance, a sensory system cannot continue to respond to a stimulus long after its termination, or we would soon cease to have discriminable images. In contrast, a memory system exists precisely to retain information in the absence of the original stimulus. Further, a memory system must have some way of retaining information concerning the time or order in which any given stimulus occurred. This is not required of a purely sensory system. The above hypothesis simply assumes that for those aspects of organization where there is no reason to expect differences between the two systems, important similarities exist.

The system underlying pitch perception has been shown to be highly structured and precisely organized. Facilitatory and inhibitory interactions taking place within it vary systematically as a function of relationships between the elements involved. An internal “tone-height” continuum has therefore been hypothesized along which various interactions occur, which in turn give rise to demonstrable psychoacoustical phenomena. Physiological studies on single units in the auditory pathway reinforce this concept by demonstrating an orderly topographical distribution of neural elements with respect to characteristic frequency, together with specific facilitatory and inhibitory interactions that mirror corresponding psychoacoustical phenomena (Harris, 1972). Our present theory therefore leads us to propose the existence of an analogous continuum underlying the retention of “tone-height” information. Interactions that are a function of distance between the interacting elements are assumed to take place along this continuum. Evidence on the transposition of tunes and chords leads to the further expectation that such a continuum would be organized logarithmically with respect to waveform frequency (Attneave & Olson, 1971).

If this hypothesis is correct, it should be possible to demonstrate interactive relationships in memory for tonal pitch, which vary precisely as a function of the pitch relationships between the elements involved. I performed a further experiment to search for such interactions (Deutsch, 1972a). The effect of a tone that formed part of a sequence interpolated between a standard and comparison tone was studied as a function of its pitch relationship to the standard tone. Subjects were required to compare two tones for pitch when these were separated by a 5-sec retention interval during which 6 other tones were played. The standard and comparison tones were taken from an equal-tempered scale and ranged over an octave, from middle C to the B above. When the standard and comparison tones differed in pitch, this was by a semitone (either higher or lower). The intervening tonal pitches, except as specified by the experimental conditions, were taken from the same scale, and varied randomly from the F# below middle C to the F an octave and half above.

There were eight conditions in this experiment. In every condition but the last, a tone whose pitch bore a critical relationship to the pitch of the standard tone was placed in the second serial position of the intervening sequence. Whenever the standard and comparison tones differed in pitch, the critical intervening tone was placed on the same side of the standard tone along the pitch continuum as the comparison tone was. The relationship between the critical intervening tone and the standard tone varied from identity to a whole-tone separation in the equal-tempered scale. A unique value of pitch separation was incorporated in each of the seven conditions, these values being placed at equal intervals of ⅙ tone within this whole-tone range. Since the musical scale is logarithmic, these intervals were also logarithmic. No such critical tone was incorporated in the eighth experimental condition, but here the pitch of the tone in the second serial position was chosen in the same way as were the other tonal pitches in the intervening sequence. The eighth condition was therefore a null condition.

The error rates in the different conditions of this experiment are plotted in Figs. 5-5 and 5-6. It can be seen that systematic interference effects do indeed occur. When the critical intervening tone is identical in pitch to the standard tone, memory facilitation is produced. Errors rise progressively with increasing pitch separation between the standard tone and critical intervening tone, peak at a separation of ⅔ tone, and decline roughly to baseline at a whole tone separation.

The maps shown in Figs. 5-5 and 5-6 were obtained by superimposing plots derived from sequences in which the standard tones were in different positions along the pitch continuum. Since the musical scale is logarithmic, an identical musical interval is based on an increased difference in waveform frequency as the scale is ascended. This difference doubles at each octave, which is the range used in this experiment. It follows that if the pitch memory store were organized in any fashion other than logarithmic, there should be a systematic shift in the peak of errors as the standard tones shift their position along the pitch continuum. For example, if the pitch memory store were linearly arranged, then as the standard tone shifted upward in pitch, the peak of errors should move progressively closer to the pitch of the standard tone on a logarithmic plot. Yet no such peak shift

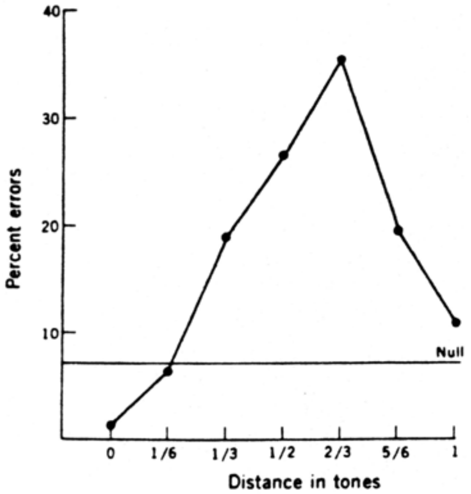


Fig. 5-5 Percent errors in pitch comparisons plotted as a function of the separation in pitch between the critical interpolated tone and the standard tone. The line labeled *Null* shows percent of errors in the control condition, where no tone closer in pitch to the standard tone than $1^{1}/_{2}$ tones was included in the intervening sequence. A separation of ⅙ tone, in the range of pitches used here, is equal to 5 Hz at the lowest standard tone pitch used, and 9 Hz at the highest. Errors were significantly fewer in the condition where the critical interpolated tone was identical in pitch to the standard tone than in the null condition ($p = .02$, two-tailed, on a Wilcoxon test). The increase in errors produced by the interpolated tone was statistically significant for each condition using a value of pitch separation within and including ⅓ tone to ⅚ tone (in each case $p < .01$, two-tailed, on a Wilcoxon test). (From Deutsch, D., 1972, by permission of *Science*, **175**, 1020-1022. Copyright 1972 by the American Association for the Advancement of Science.)

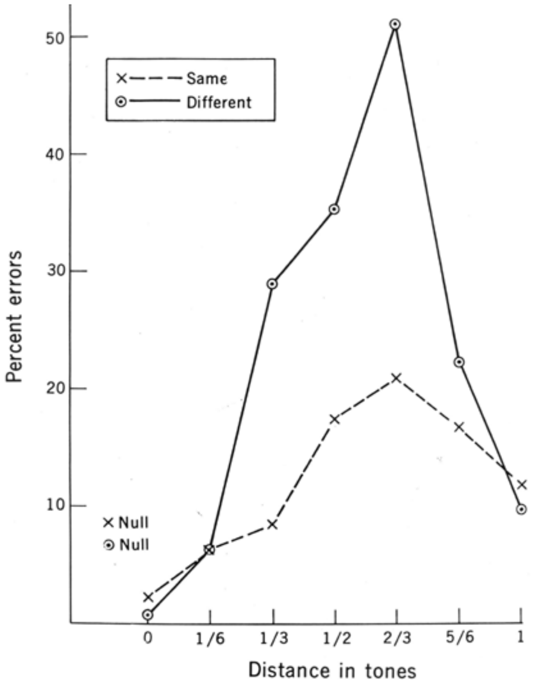


Fig. 5-6 Percent errors in pitch comparisons plotted as in Fig. 5-5, but separately by whether the standard and comparison tones were the same or different in pitch. When the standard and comparison tones differed, the critical interpolated tone was always placed on the same side of the standard tone along the pitch continuum as was the comparison tone. The two null points refer to the same control condition as described in Fig. 5-5. (From Deutsch, D., 1972, by permission of *Science*, 175, 1020-1022. Copyright 1972 by the American Association for the Advancement of Science.)

was present in the experimental records. This leads to the conclusion that the pitch memory store is laid out logarithmically, at least within the range of tonal frequencies used in this experiment.

The above study demonstrates that highly specific and systematic interactions occur within the system retaining pitch information. I explored possible bases for these effects in further experiments.

V. SPECIFIC SOURCES OF DISRUPTION IN PITCH MEMORY

It can be seen from Fig. 5-6 that the plot of errors obtained from sequences in which the standard and comparison tones differ in pitch rises much more steeply and is more sharply peaked than the plot obtained from sequences in which the standard and comparison tones are identical. One might speculate, therefore, that these two functions have different underlying bases. In order to explore this hypothesis in detail, I made a systematic study of the effects on pitch memory of including in an interpolated tonal sequence a tone that was a semitone removed from the standard tone (Deutsch, 1973a). It was found that, when the standard and comparison tones were the same in pitch, including in the intervening sequence a tone either a semitone higher or a semitone lower produced an increase in errors. Including in the same intervening sequence both a tone a semitone higher and a tone a semitone lower produced a significantly greater increase in errors (Table 5-3). Further, when the standard and comparison tones differed in pitch by a semitone, including in the intervening sequence a tone identical in pitch to the comparison tone produced a substantial

TABLE 5-3*

Condition	Percentage **Errors**
S and C Tones Same	
1. Tone a semitone higher included in intervening sequence.	7.9
2. Tone a semitone lower included in intervening sequence.	6.9
3. Two tones, one a semitone higher and the other a semitone lower, included in intervening sequence.	18.5
4. No tone a semitone higher or lower included in intervening sequence.	2.8
5. S and C tones different.	7.5

*Percent errors in pitch comparisons as a function of the presence in the intervening sequence of either one or two tones bearing a semitone relationship to the standard tone. This experiment studied the effects in sequences where the standard and comparison tones were identical in pitch. These were interspersed between sequences where the standard and comparison tones differed, and where there was no systematic inclusion or exclusion of tones on the basis of a semitone separation from the standard tone. Errors were significantly increased in both Conditions 1 and 2 compared with Condition 4; and in Condition 3 compared with Conditions 1 and 2 ($p < .01$, two-tailed on Wilcoxon tests in all cases). (From Deutsch, D., *Journal of Experimental Psychology*, 1973, **100**, 228-231. Copyright 1973 by the American Psychological Association. Reprinted by permission.

increase in errors. A significantly smaller increase in errors was produced when the critical intervening tone was a semitone removed from the standard tone, but on the opposite side of the pitch continuum to the comparison tone. Including both of these critical tones in the same intervening sequence produced a significantly greater increase in errors than including either one (Table 5-4).

This experiment demonstrates the presence of at least two separable disruptive effects on pitch memory. First, the inclusion of a tone a semitone removed from the standard tone produces a small but significant disruptive effect that cumulates in size when two such tones, one on either side of the standard tone, are included. Second, a significantly larger disruptive effect occurs when the standard and comparison tones differ in pitch, and the critical interpolated tone is identical in pitch to the comparison tone.

TABLE 5-4*

Condition	**Percentage Errors**
S and C Tones Different	
1. Tone of the same pitch as the C tone included in intervening sequence.	20.1
2. Tone a semitone from S tone, but on the opposite side of pitch continuum than C tone, included in intervening sequence.	7.4
3. Two tones, one as in Condition 1 and the other as in Condition 2, included in intervening sequence.	25.2
4. No tone a semitone removed from S tone included in intervening sequence.	3.2
5. S and C tones same.	6.6

*Percent errors in pitch comparisons as a function of the presence in the intervening sequence of either one or two tones bearing a semitone relationship to the standard tone. This experiment studied the effects in sequences where the standard and comparison tones differed in pitch by a semitone. These were interspersed between sequences where the standard and comparison tones were identical, and where there was no systematic inclusion or exclusion of tones on the basis of a semitone separation from the standard tone. Errors were significantly increased in both Conditions 1 and 2 compared with Condition 4; Condition 1 differed significantly from Condition 2; and Condition 3 differed significantly from both Conditions 1 and 2 ($p < .01$, two-tailed, on Wilcoxon tests in all cases). From Deutsch, D., *Journal of Experimental Psychology*, 1973, **100**, 228-231. Copyright 1973 by The American Psychological Association. Reprinted by permission.

Returning to the earlier study (Deutsch, 1972a), it will be recalled that here, whenever the standard and comparison tones differed in pitch, the critical intervening tone was placed on the same side of the pitch continuum relative to the standard tone as was the comparison tone. (That is, when the comparison tone was higher in pitch than the standard tone, the critical intervening tone was also higher. When the comparison tone was lower, the critical intervening tone was also lower.) The critical intervening tone was therefore identical in pitch to the comparison tone whenever these two tones bore the same relationship to the standard tone. The large error function plotted for these sequences on Fig. 5-6 could therefore also have been based on a relationship of identity or close similarity between the critical intervening tone and the comparison tone.

What could be the basis for this large disruptive effect? One might suggest that errors here are due to a deterioration of information along a temporal continuum. As a result of such deterioration, when the comparison tone is played, the subject recognizes correctly that a tone of this pitch has occurred, but assumes incorrectly that this was the standard tone. This hypothesis is described in detail elsewhere (Deutsch, 1972b). It gives rise to two predictions. First, the amount of disruption produced by the critical intervening tone should vary systematically as a function of its position in the intervening sequence. The closer the position of this critical tone relative to the standard tone, the more difficult it should be to discriminate their two positions along a temporal continuum, and so the greater should be the number of resultant confusions. Second, when this effect is plotted as a function of the pitch of the critical intervening tone relative to the pitch of the comparison tone, the peak of errors should occur when the critical intervening tone is identical in pitch to the comparison tone. Thus, a shift in the pitch of the comparison tone, when the pitch of the standard tone is held constant, should produce a parallel shift in the peak of errors produced by the critical intervening tone.

These two predictions were put to experimental test. One study measured the effect of including a tone of the same pitch as the comparison tone early as compared with late in the intervening sequence. In all the experimental trials, 6 tones were interpolated in the interval between the standard and comparison tones. In half of these sequences, the standard and comparison tones differed in pitch. A tone of the same pitch as the comparison tone was included either in the second serial position of the intervening sequence, or in the fifth, or not at all. It can be seen from Fig. 5-7 that the critical included tone produced substantially more disruption when it was includ-

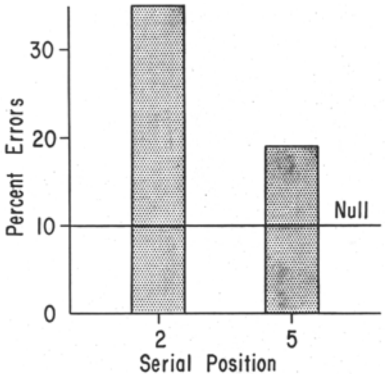


Fig. 5-7 Percent errors in pitch comparisons for sequences where the standard and comparison tones differed in pitch by a semitone, and a tone of the same pitch as the comparison tone was included in the interpolated sequence. Errors are shown separately for sequences where the critical interpolated tone was placed in the second and the fifth serial position of an interpolated sequence of 6 tones. Errors at each serial position differed significantly from baseline, and they also differed significantly from each other ($p < .01$, two-tailed, on Wilcoxon tests for all comparisons).

ed early rather than late in the intervening sequence. This is as predicted on the hypothesis of a gradual deterioration of information along a temporal continuum.

In another study the pitch of the comparison tone was varied systematically relative to the pitch of the standard tone. The standard and comparison tones differed in pitch in half of the sequences; when they differed, this was either by ⅓ tone, or by ½ tone, or by ⅔ tone. Errors were then plotted as a function of the pitch of a further tone that formed part of an interpolated sequence, using the same method as in Deutsch (1972a). The critical interpolated tone was always placed on the same side of the standard tone along the pitch continuum as was the comparison tone. That is, when the comparison tone was higher in pitch than the standard tone, the critical intervening tone was also higher; when the comparison tone was lower, the critical intervening tone was also lower. The critical intervening tone and the comparison tone were therefore identical in pitch whenever they bore the same relationship to the standard tone.

Fig. 5-8 shows the plot of errors as a function of the pitch of the critical interpolated tone relative to the standard tone, with the standard and comparison tones differing in pitch either by ⅓ tone, or by ½ tone, or by ⅔ tone. It can be seen that when the standard and comparison tones were ⅓ tone apart, errors peaked when the critical interpolated tone was also separated from the

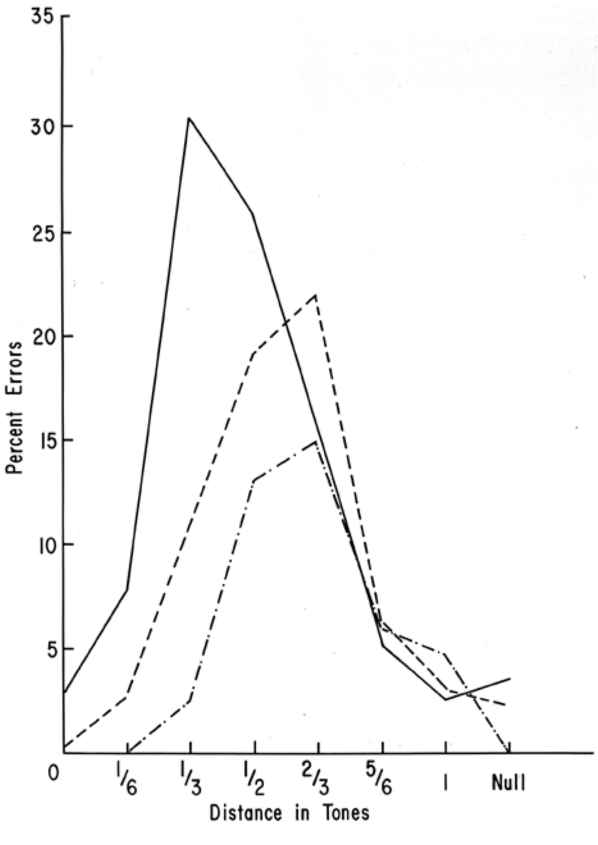


Fig. 5-8 Percent errors in pitch comparisons in sequences where the standard and comparison tones differed in pitch, and the critical interpolated tone was placed on the same side of the standard tone along the pitch continuum as was the comparison tone. Errors were plotted as a function of the amount of pitch separation between the standard tone and the critical interpolated tone, as in Figs. 5-5 and 5-6. The three separate plots show functions obtained when the standard and comparison tones were separated in pitch by ⅓ tone (—), ½ tone (- - - -), and ⅔ tone (- · - ·). For both the ½ tone and the ⅔ tone plots, errors were significantly greater when the standard tone and the critical interpolated tone were separated by ⅔ tone than when they were separated by ⅓ tone. However, for the ⅓ tone plot, errors were significantly greater when the standard tone and the critical interpolated tone were separated by ⅓ tone than when they were separated by ⅔ tone ($p < .01$, two-tailed, on Wilcoxon tests for all comparisons).

standard tone by ⅓ tone, and was therefore identical in pitch to the comparison tone. Similarly, when the standard and comparison tones were ⅔ tone apart, errors peaked when the critical interpolated tone was also separated from the standard tone by ⅔ tone. Thus a shift in the pitch of the comparison tone produced a parallel shift in the peak of errors produced by the interpolated tone. This peak shift is as predicted on the above hypothesis. However, when the standard and comparison tones were ½ tone apart, the peak of errors occurred when the critical interpolated tone was separated from the standard tone not by ½ tone but by ⅔ tone. Though the difference in errors at ⅔ tone compared with ½ tone is not statistically significant, it is noteworthy because, extrapolating from the other two curves, one would expect the difference to be in the opposite direction. A similar peak at ⅔ tone also occurs in Fig. 5-6, where the standard and comparison tones were also ½ tone apart. This suggests that some fixed disruptive effect that peaks at ⅔ tone is superimposed on the shiftable effect demonstrated by comparing the ⅓-tone curve with the ⅔-tone curve.

The functions plotted in Fig. 5-8 were derived from sessions in which the standard and comparison tones were either identical in pitch or were separated by a constant amount (*i.e.,* by either ⅓ tone, ½ tone, or ⅔ tone). In contrast to the findings in sequences where the standard and comparison tones differed, the peak of errors in sequences where they were identical remained constant at or around a separation of ⅔ tone between the standard tone and critical intervening tone, irrespective of the amount of pitch separation between the standard and comparison tones in the interspersed sequences.

The source of disruption in sequences where the standard and comparison tones are identical also behaves differently in terms of serial position. As shown in Fig. 5-9, when the standard and comparison tones are identical in pitch, the increase in errors due to interpolating a tone that is a semitone removed from the standard tone is of the same magnitude regardless of whether the critical tone is included early or late in the intervening sequence. The sequences from which this plot was derived were interspersed randomly between sequences producing the plot in Fig. 5-7. The two sets of sequences were identical in their parameters, except for whether or not the standard and comparison tones differed in pitch. This large difference in dependence on serial position therefore provides further evidence that we are studying disruptive effects of different origin.

What type of process might we invoke to account for this second source of memory disruption? In searching for analogous findings, intriguing points of similarity emerge between this and lateral inhibitory interactions that have been demonstrated both psychophysically and physi-

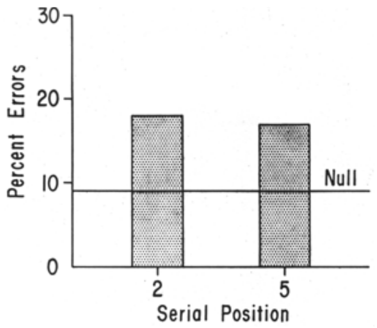


Fig. 5-9 Percent errors in pitch comparisons for sequences where the standard and comparison tones were identical in pitch, and a tone a semitone removed from the standard tone was included in the interpolated sequence. Errors are shown separately for sequences where the critical interpolated tone was placed in the second and in the fifth serial position of an interpolated sequence of six tones. Errors at each serial position differed significantly from baseline ($p < .01$, two-tailed, on Wilcoxon tests for both comparisons) but there was clearly no difference in errors upon comparing the two serial positions.

ologically in various sensory systems (Ratliff, 1965; Hartline, Ratliff, & Miller, 1961; Alpern & David, 1959; Von Békésy, 1960a, 1960b; Carterette, Friedman, & Lovell, 1969, 1970; Zwislocki, 1970; Houtgast, 1972; Sachs & Kiang, 1968; Kiang, 1968; Klinke, Boerger, & Gruber, 1969, 1970). First, the present effect cumulates when instead of one disruptive tone, two are presented, each placed on either side of the standard tone along the pitch continuum (Table 5-3; Deutsch, 1973a). Such cumulation of disruption from stimuli placed on either side of the test stimulus is typical of lateral inhibition (Ratliff, 1965). Second, the relative frequency range over which this disruptive effect occurs corresponds well with the relative frequency range over which centrally acting lateral inhibition has been found in physiological studies (Klinke *et al.,* 1969, 1970).

At this point we might wonder whether there are reasonable grounds for expecting a memory system to be subject to lateral inhibitory interactions. Two main functions have been proposed for lateral inhibition in sensory and perceptual systems. The first is sharpening the projected image (Ratliff, 1965; Cornsweet, 1970; Von Békésy, 1928, 1960a; Huggins & Licklider, 1951; Carterette *et al*., 1969, 1970). Upon consideration it can be seen that this function of sharpening should play an equally important role in a sensory memory store. We have everything to gain by mechanisms that help preserve the fineness of a memory image. The second proposed function involves the processing of higher-order information. Several such processes have been suggested to result from inhibitory as well as excitatory interactions. In vision, for instance, the responses of directionally sensitive ganglion cells in the rabbit retina are very probably influenced by lateral inhibition (Barlow & Levick, 1965). In audition, neurons in the central nervous system have been found that respond to a tone only if its frequency is changing. Often the change of frequency must be in a certain direction for a response to occur (Whitfield & Evans, 1965; Suga, 1964). It has been suggested that such behavior also results from an interplay of excitatory and inhibitory effects. If such functions are indeed performed in the case of stimuli that are presented simultaneously or near-simultaneously, they should assume at least as much importance in the case of stimuli presented successively. The system that processes higher-order tonal relationships is clearly very complex and, given what is known of neural function, extremely likely to involve inhibitory as well as excitatory interactions.

As an explanation of the present disruptive effect on pitch memory, the lateral inhibition hypothesis so far rests on three pieces of evidence: the general shape of the function, the cumulation of inhibition produced by stimuli on either side of the test stimulus along the pitch continuum, and the range within which the effect operates. A further experiment provides persuasive evidence for this hypothesis. It has been found in peripheral receptors that when a unit that is inhibiting a neighboring unit is itself inhibited by a third unit, this releases the originally inhibited unit from inhibition (Hartline & Ratliff, 1954, 1957). This phenomenon is known as disinhibition and is a property of recurrent but not nonrecurrent inhibitory networks. Thus, although it is not a necessary consequence of lateral inhibitory interactions, its demonstration should provide persuasive evidence that such a network indeed underlies the present phenomena. In our present situation, one would expect that if there were placed in the intervening sequence two critical tones, one always two-third tone removed from the standard tone, and the other further removed along the pitch continuum, then errors should be a function of the pitch relationship between the two critical intervening tones. Errors should be greatest when these two tones are the same in pitch, decline as the second critical tone moves away from the first, dip maximally at a two-third tone separation, and then return to baseline. In other words, the curve produced should be roughly inverse of the curve plotting the original disruptive effect. In an experiment to test this hypothesis, there was always placed in the second serial position of a sequence of 6 intervening tones a

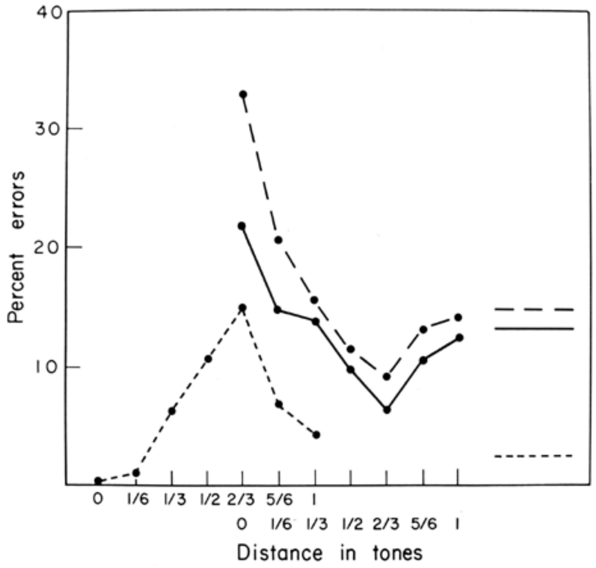


Fig. 5-10 Percent errors in pitch recognition obtained experimentally and predicted theoretically. The dotted line (· · · · ·) plots percent errors in the baseline experiment, which varies the pitch relationship between the standard tone and a critical interpolated tone. (The horizontal dotted line at right shows percent errors where no tones were interpolated within the critical range under study.) The solid line (—) displays percent errors in the experiment where a tone that is ⅔ tone removed from the standard tone is always interpolated. Errors are plotted as a function of the pitch relationship between this tone and a second critical interpolated tone that is further removed along the pitch continuum. The dashed line (- - - -) displays percent errors for the same experimental conditions predicted theoretically from the lateral inhibition model. (The horizontal solid and dashed lines at right show percent errors obtained experimentally and assumed theoretically where no further critical tone is interpolated.) When the second critical interpolated tone was identical in pitch to the first, errors were significantly enhanced compared with the baseline condition where no further critical tone was interpolated ($p < .005$, one-tailed, on a Wilcoxon test). When the second critical tone was ⅔ tone removed from the first, errors were significantly reduced compared with the baseline ($p < .01$, one-tailed, on a Wilcoxon test). Data from Deutsch, D., and Feroe, J. *Perception and Psychophysics*, in press.

tone that was two-third tone removed from the standard tone. Errors were then plotted as a function of the pitch of a further tone, placed in the fourth serial position, whose relationship to the tone in the second serial position varied systematically from identity to a whole tone separation (Deutsch & Feroe, in press).

It can be seen from Fig. 5-10 that the predicted disinhibition function was indeed obtained. The parameters of the baseline inhibitory effect were then plotted for subjects selected on the same criterion as for the disinhibition study. This function was then used to obtain a precise quantitative prediction of the disinhibition effect. These baseline and theoretically predicted disinhibition functions are also plotted on Fig. 5-10. It can be seen that there is a close correspondence between the disinhibition plots obtained experimentally and derived theoretically. This argues persuasively that the elements of the system underlying the short-term retention of tonal pitch are arranged as a lateral inhibitory network, analogous to those in systems handling incoming sensory information.

VI. MEMORY CONSOLIDATION

When a tone that is identical in pitch to the standard tone is included in an intervening sequence, its effect on memory is facilitatory rather than disruptive. A small facilitatory effect is apparent in Figs. 5-5 and 5-6, taken from a study in which the subjects had been selected for displaying a very low baseline error rate, so as to permit accurate plotting of the disruptive effects.

With higher baseline errors, a substantial and highly significant reduction in errors is produced by the repeated tone, both in sequences where the standard and comparison tones are identical in pitch, and also where they differ (Deutsch, 1970c, 1972b).

This facilitatory effect is highly sensitive to serial position. In one experiment, a sequence of 6 tones was interpolated between the standard and comparison tones. A tone of the same pitch as the standard tone was included either in the second serial position of the intervening sequence, or in the fifth, or not all. Fig. 5-11 shows the serial position effect for sequences in which the standard and comparison tones are identical in pitch, and Fig. 5-12 shows the effect when they differ. It can be seen from both plots that errors are reduced substantially more when the standard tone is repeated early rather than late in the intervening sequence. Indeed, for each plot the reduction in errors is statistically significant only for sequences in which the repeated tone occurs in the early serial position (Deutsch, in press).

This serial position effect is similar to the effect shown in Fig. 5-9, which plots the errors produced by including a tone that is identical in pitch to the comparison tone, when the standard and comparison tones differ in pitch. One may hypothesize that these two effects are based on the same process—the spread along a temporal continuum of the distributions representing the component tones, with their resultant overlap and summation. This line of argument is developed in detail elsewhere (Deutsch, 1972b). If this hypothesis is correct, the repeated tone produces consolidation of memory for the standard tone by trace enhancement. Such an effect would also be expected to occur proactively. Alternatively, the decrease in errors here produced by the repeated tone might be due to the subject's adopting a particular strategy. When the standard tone is repeated, the subject recognizes it, and as a result holds the new trace rather than the old one in memory; that is, the repeated tone becomes the new standard tone. In this way, both the number of intervening items and the retention interval are effectively reduced, and so errors are decreased. To control for this possibility, a further experiment was performed. The interpolation of a sequence of 4 randomly chosen tones (Condition 1) was compared with the interpolation of 6, in which a tone of the same pitch as the standard tone was included in the second serial position (Condition 2) and with the interpolation of 6 randomly chosen tones (Condition 3). Thus in the

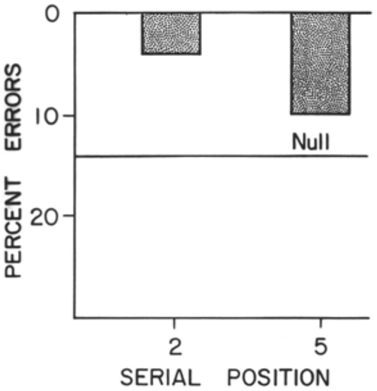


Fig. 5-11 Percent errors in pitch comparisons where the standard and comparison tones were identical in pitch, and a further tone of identical pitch was included in the intervening sequence. Errors are shown separately for sequences where the critical interpolated tone was placed in the second and in the fifth serial position of an interpolated sequence of 6 tones. Errors at the second serial position differed significantly from baseline ($p < .01$, two-tailed, on a Wilcoxen test) but errors at the fifth serial position did not. A significant difference was manifest between errors at the second and the fifth serial positions ($p < .01$, two tailed, on a Wilcoxon test). Data from Deutsch, D., *Memory and cognition*, in press.

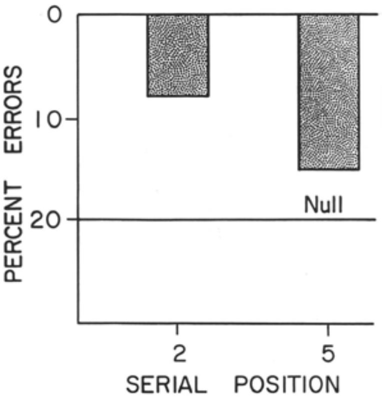


Fig. 5-12 Percent errors in pitch comparisons where the standard and comparison tones differed in pitch, and a tone of identical pitch to the standard tone was included in the interpolated sequence. The same pattern of significances occurred here as in Fig. 5-11. Data from Deutsch, D., *Memory and Cognition*, in press.

first two conditions, an identical retention interval and an identical number of interpolated tones separated the standard from the comparison tone (Fig. 5-13). If the facilitatory effect of repeating the standard tone were due to the subject adopting the repeated tone as the new standard, no difference in performance between Conditions 1 and 2 should be expected. However, if the repeated tone produced true consolidation, errors should be fewer in Condition 2 although here the number of interpolated tones in the total sequence was in fact larger. It can be seen from Fig. 5-13 that the hypothesis of true consolidation is borne out. Errors in Condition 2 are fewer than in either Condition 1 or Condition 3.

According to the three-stage model of memory, consolidation processes occur only when the information is coded or labeled. Indeed, consolidation is assumed to take place only when the information is in a form suitable for long-term storage. Turvey (1967) describes an experiment that he interprets as evidence for this view. Using the partial report procedure, he presented digit slides tachistoscopically for 50 msec. When one slide was repeated 54 times with other slides interpolated between repetitions, no cumulative effect of repetition was found. This result contrasts with the present finding of consolidation in sensory memory. However, the interpolated nonrepeated slides could well have interfered with the sensory trace, as might be expected from the findings of Steffy and Ericksen (1965). Such interference could have prevented memory cumulation due to repetition in this situation. But whatever the interpretation of Turvey's negative results, the present findings represent an example of consolidation in sensory memory.

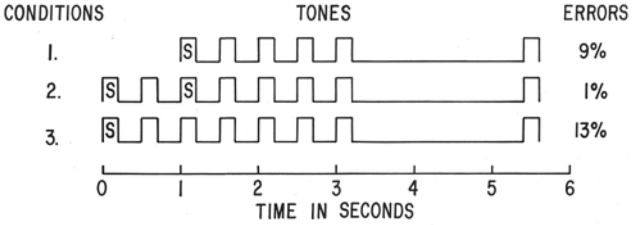


Fig. 5-13 Percent errors in pitch comparisons as a function of number of interpolated tones and repetition of the standard tone pitch. The symbol "S" stands for the pitch of the standard tone. Errors in Condition 3 were significantly greater than in Condition 1, yet errors in Condition 2 were significantly fewer than in either Conditions 1 or 3 ($p < .01$, two-tailed, on Wilcoxon tests for all comparisons). Data from Deutsch, D., *Memory and cognition*, in press.

VII. TONE HEIGHT AND TONE CHROMA

There is abundant evidence that we code information concerning tonal pitch not only along a monotonic dimension of "tone height" but also in terms of its position within an abstracted octave. Tones that are separated by octaves, *i.e.*, whose waveform frequencies stand in the ratio of a power of 2:1, have long been known to have an essential similarity. Indeed, the musical scale is based on this similarity, since tones separated exactly by octaves are given the same name (C, C#, D, *etc*.) People with absolute pitch may often name a note correctly but place it in the wrong octave (Baird, 1917; Bachem, 1954). Octave generalization in response to tonal stimuli has been demonstrated not only in man (Humphreys, 1939) but even in the rat (Blackwell & Schlosberg, 1943). A complex tone made up of components separated by octaves sounds like a single organ-like tone rather than like a chord (Shepard, 1964). Inverted chords (*i.e.*, chords in which the component tones have the same name but are placed in different octaves) are treated in traditional music as harmonically equivalent to their root forms (Rimsky-Korsokov, 1930); they do indeed sound strikingly similar. (To be strictly accurate, the subjective octave is slightly larger than the physical octave, and also varies slightly as a function of frequency (Ward, 1954). This does not, however, affect the general argument).

Given such considerations, various investigators have maintained that tonal pitch should not be treated as a unidimensional stimulus, but should rather be analyzed along two dimensions: *i.e.*, tone height, which represents overall pitch level, and tone chroma, which defines the pitch of a tone within the octave (Meyer, 1904, 1914; Révész, 1913; Ruckmick, 1929; Bachem, 1948; Shepard, 1964). Various bases have been suggested for this bidimensional representation. For instance, it has been proposed that tonal pitch be represented as a helix, with tones separated by an octave lying in closest proximity within each turn of the helix (Drobisch, 1846). A similar suggestion involving a bell-shaped spiral instead of a helix has been made (Ruckmick, 1929).

The problem, however, with hypothesizing a single three-dimensional array to accommodate both "tone height" and "tone chroma" is that this would predict octave generalization in all musical situations. Yet the evidence from music indicates that although simultaneously presented tonal combinations are invertible, successive tonal combinations are not. This question can also be tested experimentally. If successive intervals involving notes of the same name but placed in different octaves were treated by us as equivalent, then we should be able to use octave generalization to recognize tunes. But if inverted successive intervals were treated as independent entities, we should be unable to do this. Reasoning along these lines, I performed the following experiment. I played the first half of the tune *Yankee Doodle* to groups of people in any one of three octaves, and it was universally recognized. Yet when I played the same sequence in identical fashion, except that each note was chosen randomly from one of the same three octaves, the percentage correct recognition was not significantly different from that obtained when the sequence was played as a series of clicks with the pitch information omitted but the rhythmic information retained (Deutsch 1972a). It must be concluded that tune recognition takes place along a channel that is independent of that which gives rise to octave generalization.

Elsewhere I have proposed a scheme for the abstraction of tonal relationships that accommodates both "tone-chroma" phenomena and also the finding that octave generalization does not occur in tune recognition (Deutsch, 1969). According to this scheme, abstraction of tonal information takes place along two independent channels, each of which consists of two stages of information transformation (Fig. 5-14). The first channel is concerned with tonal transposition, and is described in detail later. The second channel underlies "tone-chroma" phenomena. In the first

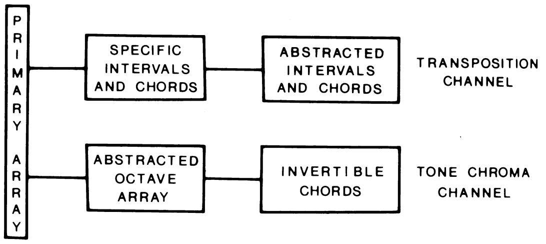


Fig. 5-14 Flow diagram for abstraction of pitch relationships. On this scheme, the information is simultaneously transformed along two parallel channels, one forming the basis for transposition phenomena, and the other for "tone-chroma" phenomena. It is assumed that the information at each stage of both channels is stored in a unique fashion. (Adapted from Deutsch, D., *Psychological Review*, 1969, **76,** 300-307. Copyright 1969 by the American Psychological Association. Reprinted by permission.)

stage of transformation along the "tone-chroma" channel, there is convergence of frequency-specific units onto second-order units in such a way that units responding to tones separated exactly by octaves are joined together (Fig. 5-15). This second-order array thus provides a basis for the "tone-chroma" dimension. In the second stage of transformation along this channel, second-order units are joined to third-order units, which respond only to simultaneous input. This third-order array thus provides for chord inversion. It is further assumed that each of these memory arrays has its own retention characteristics, in terms of susceptibility to specific interference effects, rate of decay, consolidation patterns, *etc*. From an everyday knowledge of music it would appear that the higher-order the array, the more enduring its memory characteristics.

One may ask whether disruptive effects on immediate memory for tonal pitch take place along the dimension of "tone height," "tone chroma," or both. This question can be investigated by studying the possible generalization patterns across octaves for these interference effects. Such octave generalization would be evidence for the involvement of a "tone-chroma" dimension.

In one experiment, I found that large disruptive effects in pitch recognition were produced by interpolating tones taken from the octave above or below the octave from which the standard and comparison tones were taken (Deutsch, 1973c). In a further experiment, I studied the effect of interpolating tones in the intervening sequence that bore the same relationship to the standard and comparison tones as had been found earlier to produce disruption, but that were further

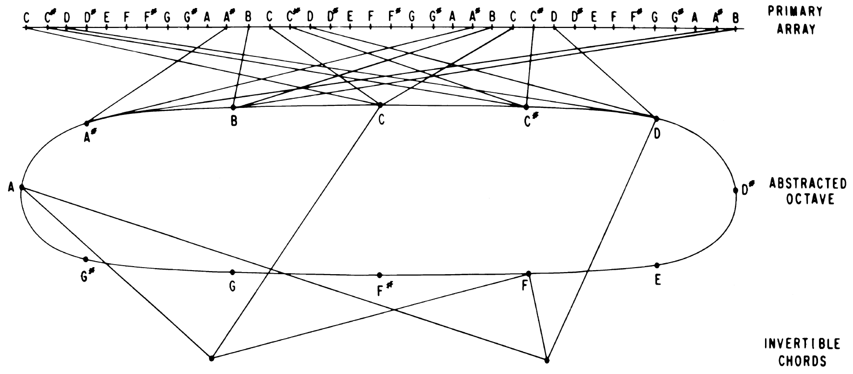


Fig. 5-15 Confluence of information along the two stages of the "tone chroma" channel. Units corresponding to the traditional musical scale are here used for purposes of clarity, but these simply represent arbitrary points on a continuum of log frequency. (Adapted from Deutsch, D., *Psychological Review*, 1969, **76,** 300-307. Copyright 1969 by the American Psychological Association. Reprinted by permission.)

removed by an octave (Deutsch, 1973b). Two sources of interference were used. The first was that produced by the interpolation of two tones, one a semitone higher than the standard tone, and the other a semitone lower, when the standard and comparison tones were identical in pitch (Deutsch, 1973a). The second was that produced by the interpolation of a tone of the same pitch as the comparison tone, when the standard and comparison tones differed in pitch (Deutsch, 1970b, 1972b, 1973a).

It was found that both sources of interference exhibit octave generalization. It can be seen from Table 5-5 that the generalization from the higher octave is extremely strong, and that from the lower octave, though statistically significant, is weaker. The finding of substantial and significant octave generalization demonstrates the involvement of a "tone-chroma" dimension in these effects. However, the finding that such generalization is not absolute demonstrates that these effects also take place along a "tone-height" dimension. In terms of the scheme described above (Deutsch, 1969), it would appear that these interactions take place along both the primary array and the abstracted octave array (Fig. 5-15). At all events, one must conclude that the memory store within which such interactions take place is bidimensional in nature.

VIII. INTERACTIONS WITH THE SYSTEM RETAINING PITCH RELATIONSHIPS

It is clear from an analysis of music recognition that memory for tonal relationships must exist independently of memory for the component tonal pitches. Pairs of tones appear to stand in the same relationship to each other when their waveform frequencies are related by roughly the same ratio. The question of whether this equivalence is based on pure ratios or some approximation of these ratios is a matter of current debate, but does not affect the general principle of trans-

TABLE 5-5*

Conditions	Percentage Errors
S and C Tones Different	
1. No tone at pitch of C tone, or displaced by an octave from C tone, included in intervening sequence.	4.6
2. Tone at pitch of C tone included in intervening sequence.	26.7
3. Critical included tone as in Condition 2, but displaced an octave higher.	20.2
4. Critical included tone as in Condition 2, but displaced an octave lower.	12.1
S and C Tones Same.	
5. No tone a semitone removed from S (and C) tone, or displaced from such a tone by an octave, included in intervening sequence.	5.6
6. Two tones, one a semitone higher and the other a semitone lower, included in intervening sequence.	24.4
7. Critical included tone as in Condition 6, but displaced an octave higher.	21.0
8. Critical included tone as in Condition 6, but displaced an octave lower.	11.3

*Percent errors in pitch comparisons as a function of the presence in the intervening sequence of tones displaced by an octave from those known to produce disruption. Errors in sequences where the disruptive tones were displaced by an octave were significantly greater than baseline errors for all conditions ($p < .01$, two-tailed, on Wilcoxon tests in all cases). A weaker pattern of generalization from the lower compared with the higher octave was also manifest: significant differences occurred between Conditions 3 and 4 ($p < .02$, two-tailed, on a Wilcoxon test) and Conditions 7 and 8 (p < .01, two-tailed, on a Wilcoxon test). From Deutsch, D., 1973, by permission of *Perception & Psychophysics*, **13,** 271-275. Copyright 1973 by The Psychonomic Society, Inc.

position. Plomp, Wagenaar, & Mimpen (1973) have shown, however, that we do not rate intervals for similarity on the basis of their relative ranks on a scale of ratio simplicity. At all events, when tonal combinations are transposed from one key to another, the component tonal pitches are altered, but the relationships between them remain the same. It is these relationships that are stored in memory and provide the basis for transposition. Under such circumstances, provided sufficient time or interfering activity occurs between the initial presentation of the combination and its later presentation in transposed form, the combination will be recognized as the same and the fact of its transposition may go unnoticed. This finding leads to the conclusion that memory for abstracted tonal relationships is more enduring than memory for the pitches of the component tones. Attneave and Olson (1971) have demonstrated that even musically untrained subjects will transpose successive tonal relationships in a log frequency medium, especially when they can use enduring long-term traces for the abstracted tonal information.

According to the above scheme for abstraction of pitch information, transposition takes place in two stages along one of two parallel channels (Fig. 5-16). In the first stage, frequency-specific units converge onto second-order units in groups of two or three. These second-order units therefore respond to intervals and chords only when they are formed by tones of specific pitch. Second-order units responding to two-tone combinations fall into three categories: those responding to simultaneous tonal combinations, those responding to ascending intervals, and those responding to descending intervals. In the second stage of transformation along the transposition channel, second-order units are joined to third-order units in such a way that there is convergence of units responding to a given tonal relationship. The third-order units therefore respond to the abstracted relationships independently of the component pitches involved. This third-order array thus provides the basis for transposition.

As with the parallel "tone-chroma" channel, it is assumed that each of the proposed memory arrays along the transposition channel exhibits a unique set of retention characteristics. Again, it is expected that the higher-order the array, the more enduring its retention characteristics. For example, we remember and learn melodies much better than we remember or learn what key they are played in. It follows that the abstracted information concerning the successive tonal relationships is learned and retained much better than the information concerning the absolute pitches of the component tones. In terms of the present scheme, the third-order array along the transposition channel retains information much longer, and has the power to consolidate information much more efficiently than does the primary array. Similar considerations apply to transposed chords.

In further studies the retention of abstracted tonal relationships in immediate memory was explored (Deutsch & Roll, in press). The paradigm used was very similar to that used in previous experiments, except that the standard and comparison tones always occurred simultaneously with other tones of lower pitch. The two tones of each combination were fed separately to each

Fig. 5-16 Confluence of information along the two stages of the transposition channel. As in Fig. 5-15, units corresponding to the traditional musical scale are here chosen solely for the purposes of clarity. (Adapted from Deutsch, D., *Psychological Review*, 1969, **76,** 300-307. Copyright 1969 by the American Psychological Association. Reprinted by permission.

ear, so as to avoid the introduction of artifacts into the physical stimulus. On each trial the standard and comparison tonal combinations were separated by a sequence of 6 intervening tones. The subject was instructed to listen to the upper tone of the first combination and ignore the lower tone, to ignore the 6 intervening tones, and then to judge whether the upper tone of the second combination was the same or different in pitch from the upper tone of the first combination. The standard tone was always separated by 7 semitones (*i.e.*, a musical fifth) from its accompanying partner. However, the relationship between the comparison tone and its partner varied.

In the first experiment, two conditions were compared in which the standard and comparison tones were the same in pitch. In the first condition, the tone accompanying the comparison tone was the same in pitch as the tone accompanying the standard tone. In the second condition the lower tone shifted either upward or downward in pitch by a semitone. As shown in Table 5-6, errors were substantially more numerous in the second condition than in the first. This is consistent with an interpretation in terms of misjudgement of the comparison tone based on its altered relationship to its accompanying tone. However, the subjects might have been mistakenly judging the wrong tone. So in a further study the subjects were required to judge not only whether the standard and comparison tones differed in pitch, but also the direction in which they differed. No correlation was found between the direction of incorrect "different" judgments and the actual direction in which the lower tones of the combinations varied.

Two conditions were compared in which the standard and comparison tones differed in pitch. In the first condition, the tone accompanying the comparison tone was the same in pitch as the tone accompanying the standard tone. In the second condition it shifted in parallel with the pitch difference between the standard and comparison tones. That is, when the comparison tone was a semitone higher than the standard, the accompanying tone was also a semitone higher. When the comparison tone was a semitone lower, the accompanying tone was also a semitone lower. In this way the interval formed by the simultaneous combination was preserved. As shown in Table 5-6, errors were substantially greater in the second condition than in the first. In this case, the increased errors could not have been due to the subjects' mistakenly judging the wrong tone,

TABLE 5-6*

Conditions	**Percentage Errors**
S and C Tones Same	
1. Simultaneous tone same.	10
2. Simultaneous tone different.	29
S and C Tones Different	
1. Simultaneous tone same.	21
2. Simultaneous tone moves in parallel with an upward shift of the comparison tone.	16
3. Simultaneous tone moves in parallel with a downward shift of the comparison tone.	26

*Percent errors in pitch comparisons as a function of the relationships between the standard and comparison tones and their accompanying partners. When the standard and comparison tones were the same in pitch, errors increased when the accompanying tone shifted in pitch. When the comparison tone differed in pitch from the standard tone, errors increased when the accompanying tone moved in the same direction, thus preserving the relationship within the combination ($p < .01$ in both cases).

All standard tone combinations form a musical fifth. All shifts are of one semitone. Data from Deutsch, D., and Roll, P. L., *Journal of Experimental Psychology*, in press.

since both tones of the combination moved in the same direction. This provides strong evidence that misrecognition was based on the storage of abstracted relational information.

It might alternatively be argued that when the lower tones of the test tone combinations were the same in pitch, these lower tones served as some kind of anchor to facilitate discrimination of the standard from the comparison tone. I therefore performed another experiment that was essentially a replication of the first, except that the two tones of the test-tone combinations moved in opposite directions rather than in parallel. That is, when the comparison tone was a semitone higher than the standard tone, its accompanying tone shifted downward by a semitone. When the comparison tone was a semitone lower, its accompanying tone shifted a semitone upwards. Here a very interesting finding emerged. It will be recalled that a “fourth” is a musical inversion of a “fifth.” When the two components of the combination shifted toward each other, the relationship between them changed from a “fifth” to a “fourth.” When they shifted away from each other, the new relationship became a “sixth.” It was found that errors were significantly greater when the two components of the combination shifted inward than when they shifted outward. That is, errors increased when the comparison tone combination stood in the same abstracted and inverted relationship as the standard tone combination (Table 5-7). It would appear that errors here were based on the storage of a tonal relationship that was both transposed and inverted.

To ensure that these results were not due to verbal labeling of the intervals, the subjects were asked at the end of the experiment to name the intervals used. Because none of them was able to do this, it must be concluded that the pattern of errors was due to the retention of information that was abstracted and yet not verbally labeled.

The above experiment may be related to an interesting study by Plomp *et al.* (1973), who examined patterns of confusion in judgments of intervals that varied in semitone steps between a minor second and an octave. They found that subjects generally confused intervals on the basis of their size; however, the subjects tended in addition to confuse intervals that were inverted. That is, a “fifth” and a “fourth” were confused with each other more than either with a “diminished

TABLE 5-7*

Conditions	Percentage Errors
S and C Tones Same	
1. Simultaneous tone same.	8
2. Simultaneous tone different.	29
S and C Tones Different	
1. Simultaneous tone same.	18
2. Simultaneous tone moves in opposite direction to an upward shift of the comparison tone.	31
3. Simultaneous tone moves in opposite direction to downward shift of the comparison tone.	31

*Percent errors in pitch comparisons as a function of the relationships between the standard and comparison tones and their accompanying partners. As on Table 5-6, when the standard and comparison tones were the same in pitch, errors increased when the accompanying tone shifted in pitch ($p < .01$). When the standard and comparison tones differed, shifting the pitch of the accompanying tone in the opposite direction produced no overall effect. However, in sequences where the accompanying tones shifted, the error rate was significantly enhanced when the comparison combination formed a relationship that was an inversion of the relationship formed by the standard combination ($p < .05$).

All standard tone combinations form a musical fifth. All shifts are of one semitone. Data from Deutsch, D., and Roll, P. L., *Journal of Experimental Psychology*, in press.

fifth." Confusions between "seconds" and "sevenths," and between "thirds" and "sixths," also emerged. This experiment provides further evidence for storage of inverted intervals.

IX. CONCLUSION

In conclusion, various general questions concerning nonverbal memory are considered in light of these experiments. The first concerns the amount of differentiation within the precategorical information storage system. It was initially assumed that all precategorical information was retained in a single nonspecific large-capacity store (Broadbent, 1958). Then, as evidence accumulated that nonverbal memory exhibited modality-dependent characteristics, the nonverbal storage system was divided into several stores, separated on the basis of input modality alone (Atkinson & Shiffrin, 1968). However, the characteristics of memory for tonal pitch show separation by input modality to be insufficient. The acoustical properties of words interfere only minimally with memory for tonal pitch, whereas other tones interfere considerably. Further, it is clear on general grounds that memory for abstracted tonal relations is considerably more enduring than memory for absolute pitch values. A more realistic principle for subdividing precategorical memory would appear to be by the type of perceptual operation performed on the information, rather than by the nature of the end-organ involved.

A related question concerns the nature of the influence producing forgetting in nonverbal memory. Various diffuse factors, such as decay or displacement, have been proposed (Broadbent, 1958; Crowder & Morton, 1969). However, the experiments described here show interference in memory for tonal pitch to be a systematic function of similarity between the tone to be remembered and the interfering tone. Indeed, the evidence strongly indicates that interactive effects in pitch memory are analogous to known effects operating in systems handling incoming sensory information. On this basis it is here proposed that the memory system that retains sensory information is organized in many ways along the same principles as the system that receives it.

A final question concerns the form of information storage required for consolidation. It is generally held that consolidation processes occur only when information has been coded verbally in a form suitable for long-term storage. However, experiments described here demonstrate consolidation through repetition in memory for the pitch of a single tone. This argues strongly against the view that a specific type of coding is necessary for memory consolidation.

In conclusion, the findings described in this chapter show that the short-term retention of tonal pitch is the function of a system possessing a high degree of organization and specificity. It is likely that similar characteristics will be uncovered in other sensory memory systems.

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