Memory for Nonverbal Auditory Information: A Link between Behavioral and Physiological Studies

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6

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Introduction

When objects and events are represented in memory, much of this representation must be in terms of dimensions of variation. Thus, the representation of visually perceived objects must include colors, brightnesses, locations, and so on. The representation of sounds must analogously include pitches, durations, loudnesses, and locations. Such representational dimensions need not be confined to first-order attributes. Lines are perceived as having length, curvature and orientation; at a higher level, objects are perceived as having such characteristics as volume and distance. Pitch sequences may be described at one level as a succession of melodic and harmonic intervals, and at a higher level in terms of steps along scalar alphabets (Deutsch & Feroe, 1981). Certain complex attributes appear to be internally represented in terms of several dimensions. For example, the perceptual space for musical timbre appears to be bi- or tridimensional (Grey, 1975; Risset & Wessel, 1982).

Let us assume that an incoming stimulus gives rise to a memory representation in terms of values along several different dimensions. A number of general questions may then be posed: How do such memory dimensions relate to physical dimensions? How do the different elements of a given memory dimension interact with one another? How do the outputs of different memory dimensions interact in retrieval? And so on. To examine these questions, the system underlying memory for pitch and pitch relationships was investigated. The findings reveal the existence of a finely tuned multidimensional memory system, which displays characteristics that are formally analogous to those found in systems handling sensory information at the incoming level, and whose physiological substrates are well understood.

Memory for Pitch: General Considerations

A number of hypotheses may be advanced concerning the characteristics of pitch memory. One is that pitch memory is the function of an unstructured buffer store, in which information deteriorates simply through a process of temporal decay. A second hypothesis

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is that pitch information is retained in a general store of limited capacity, and that memory loss occurs as a result of such capacity limitation. A third hypothesis is that pitch memory is the function of a specialized system, whose elements interact in a systematic fashion.

In order to decide between these various hypotheses, we may begin with the following set of observations. Suppose that a tone is presented, and this is followed shortly by another tone that is either identical in pitch or that is a semitone removed. Most listeners have no difficulty in determining whether these two tones are the same or different. When a pause of 6 seconds' duration is interpolated between the tones to be compared, the judgment is still a very easy one. Various investigators have shown that memory for pitch is subject to a process of temporal decay (Bachem, 1954; Harris, 1952; Koester, 1945; Wickelgren, 1966, 1969); however, in the present situation, the difference in pitch to be discriminated is so large that the decay is not subjectively apparent. Suppose now that eight extra tones are interpolated between the two to be compared, and the listener is asked to ignore them. The task now becomes strikingly more difficult. In fact, if listeners are selected for errorless performance in comparing such tone pairs when these are separated by a silent retention interval of 6 seconds, they will typically make over 40% errors when eight extra tones are interpolated during the retention interval.

We can conclude that the system underlying memory for pitch is one in which information is subject to a slow rate of temporal decay, but is also subject to a sizable interference effect produced by interpolated tones. This leads us to inquire as to the cause of this interference effect, and again various hypotheses may be considered. The first is that attention to the tone to be remembered is necessary to prevent memory decay, and that the interpolated tones produce attention distraction. If this were the case, then other interpolated materials that distract attention should also produce memory loss. A second hypothesis is that pitch information is retained in a general memory store together with other types of material, and that this store is of limited capacity. We should then expect that other interpolated materials would produce memory impairment, provided that they entered memory. A third hypothesis is that pitch information is retained in a specialized system, and that memory impairment results from interactions within this system.

An experiment was performed to decide between these various hypotheses (Deutsch, 1970). In one condition, subjects compared the pitches of two tones, which were separated by a retention interval during which six extra tones were interpolated. The test tones either were identical in pitch or differed by a semitone. The second condition was the same as the first, except that six spoken digits were interpolated instead of tones. In both these conditions, subjects were asked to judge whether the test tones were the same or different in pitch, and to ignore that interpolated materials. The third condition was identical to the second, except that the subjects were asked to recall the digits in addition to comparing the pitches of the test tones. This ensured that the digits were attended to and were committed to memory. In the fourth condition, digit recall was required alone.

The interpolated tones were found to produce a substantial increase in errors of pitch recognition. However, the interpolated digits produced only a minimal decrement, even when their recall was required. Further, the requirement to perform the pitch-recognition task did not produce an increase in errors of digit recall. We can conclude from this experiment that the impairment of memory for pitch that occurs when other tones are interpolated is the result of interactions within a specialized system.

Lateral Inhibition in the Pitch-Memory System

We now inquire more specifically into the nature of the interactions that result in loss of memory for pitch. One possibility is that tones are retained in a store that is limited in terms of the number of tones that it can hold at any one time. When new tones enter this store, old ones are bumped out. On this hypothesis, the amount of memory impairment produced by an interpolated tone would be the same, regardless of its pitch relationship to the tone to be remembered. However, if the effect of one tone on memory for another were found to vary as a function of their pitch relationship, then this would indicate instead a system in which memory elements interact in a specific fashion.

In one experiment to evaluate these two hypotheses (Deutsch, 1972b), subjects were presented with a test tone, which was followed by six interpolated tones, and then by a second test tone. The pitches of the test tones either were identical or differed by a semitone. The experiment investigated the effects of placing in the second serial position of the interpolated sequence a tone whose pitch bore a critical relationship to that of the first test tone. This relationship varied in steps of 1/6 tone between identity and a whole-tone separation.

The results of the experiment are displayed in Figure 6-1. It can be seen that the error rate varied systematically, depending on the degree of similarity between the first test tone and the critical interpolated tone. When these two tones were identical in pitch, memory was facilitated. Errors increased gradually as the pitch difference between the first test tone and the critical interpolated tone increased. Errors peaked at a difference of 2/3 tone, and then decreased, reaching baseline at around a whole-tone separation.

The plot displayed in Figure 6-1 was obtained by superimposing plots from sequences in which the test tones were positioned at different points along the pitch continuum, spanning a range of an octave. Since the musical scale is a logarithmic function of waveform frequency, an identical difference along this scale is based on an increasing

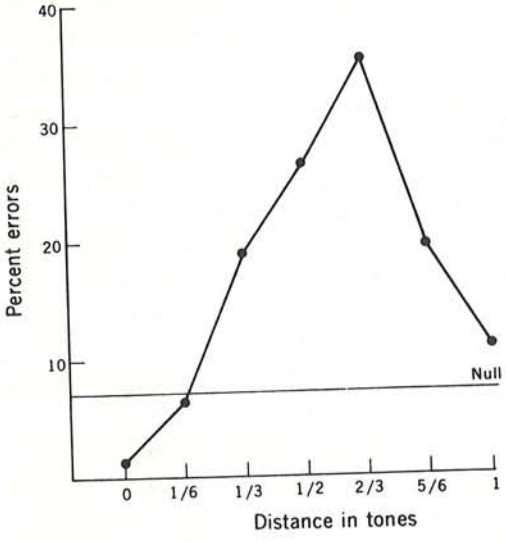

FIGURE 6-1. Percentage of errors in pitch-comparison judgment as a function of the distance in pitch between the first test tone and a critical interpolated tone. The line labeled *Null* indicates the percentage of errors in a control condition, in which all interpolated tones were at least 1½ tones removed in pitch from the first test tone. (From D. Deutsch, Mapping of interactions in the pitch memory store. *Science*, 1972, *175*, 1020–1022. Copyright 1972 by the American Association for the Advancement of Science. Reprinted by permission.)

frequency difference as the scale is ascended; this difference doubles over an octave. In the present experiment, the error rate varied systematically as a function of the log frequency difference between the interacting tones, and this was independent of their absolute position along the scale. Given this finding, it was proposed that pitch information is retained along an array whose elements are activated by tones of specific pitch. Elements that are activated by tones whose fundamental frequencies are separated by the same distance in log frequency units are spaced the same distance apart on this array. It was further hypothesized that interactions occur along this array which are a function of the distance between the interacting elements.

But what might be the physiological basis of these interactions? An interesting analogy here presents itself with lateral inhibitory interactions found in systems that handle sensory information at the incoming level (Alpern & David, 1959; Carterette, Friedman, & Lovell, 1970; Hartline, Ratliff, & Miller, 1961; Klinke, Boerger, & Gruber, 1970; Ratliff, 1965; Sachs & Kiang, 1968; Von Békésy, 1960). Indeed, the relative frequency range over which the present interference effect was found to occur corresponds well with the relative frequency range over which centrally acting lateral inhibition has been found in physiological studies of the auditory system (Klinke *et al.*, 1970). As further evidence, the present effect was found to cumulate when two interpolated tones were presented in this disruptive range, placed one on either side of the test tone along the pitch continuum (Deutsch, 1973). Analogously, in lateral inhibitory networks, a cumulation of inhibition occurs from stimuli that are placed one on either side of a test stimulus (Ratliff, 1965).

If a lateral inhibitory network were indeed involved, an effect might be expected that would be most unlikely to occur on other grounds. It has been found in some physiological studies that when a neural unit that is inhibiting another unit is itself inhibited by a third unit, there is a release of the originally inhibited unit from inhibition. This phenomenon is known as disinhibition, and is a property of recurrent but not nonrecurrent lateral inhibitory networks. The demonstration of disinhibition should thus provide convincing evidence that a lateral inhibitory network underlies the present memory effects.

More specifically, one might expect that if a tone that was inhibiting memory for another tone were itself inhibited by a third tone, memory for the first tone would return. That is, in sequences where the test tones are identical in pitch, if two critical tones were interpolated—one always 2/3 tone removed from the first test tone, and the other further removed along the pitch continuum—then the error rate should vary systematically as a function of the pitch relationship between these two interpolated tones. As indicated by the open circles in Figure 6-2, the error rate should be greatest when these two tones are identical in pitch, should decline as the second test tone moves away from the first, should dip maximally at a separation of 2/3 tone, and then should return to baseline. The plot produced should thus be roughly the inverse of the plot produced by the original disruptive effect.

This experiment was performed, and the results are displayed by the closed circles in Figure 6-2 (Deutsch & Feroe, 1975). The open circles display the function that was obtained theoretically from the baseline function shown by the open triangles, assuming a lateral inhibitory network. It can be seen that there is a very good correspondence between the experimentally and theoretically obtained functions. This provides strong evidence that elements of the pitch-memory system are arranged as a recurrent lateral inhibitory network.

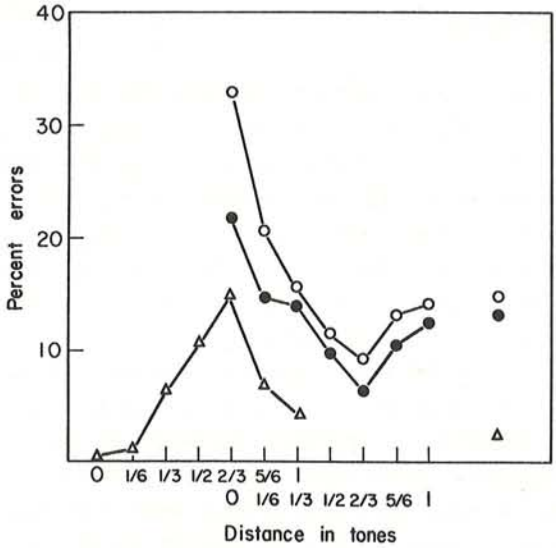

FIGURE 6-2. Percentages of errors in pitch recognition obtained experimentally and predicted theoretically from the model of lateral inhibition. See text for details. (From D. Deutsch & J. Feroe, Disinhibition in pitch memory. *Perception and Psychophysics*, 1975, *17*, 320–324. Copyright 1975 by The Psychonomic Society, Inc. Reprinted by permission.)

We may then ask why such a system should have evolved; that is, in what ways it might be useful to the organism. In the case of systems that handle sensory information at the incoming level, two main functions for lateral inhibition have been postulated. The first is a sharpening of the sensory image (Cornsweet, 1970; Ratliff, 1965). Such a sharpening effect would clearly be valuable in preserving the fineness of a memory image as well. The second function concerns that abstraction of higher-order information. For example, Barlow and Levick (1965) have proposed that the responses of directionally sensitive ganglion cells in the rabbit retina are very likely to be influenced by lateral inhibition. If this type of information abstraction is performed in the case of stimuli that are presented simultaneously or near-simultaneously, than it is also likely to be performed in the case of stimuli that are presented in temporal succession. Thus it would appear that lateral inhibition is a useful feature to have built into a memory system.

A more general point should also be made in this context. From the evidence described, the system that retains pitch information appears to be organized in certain important respects along the same lines as the system that handles such information at the incoming level. We can therefore envisage the former system in terms of a direct projection from the latter. This view contrasts with the concept of a rapidly deteriorating "preperceptual" buffer store, in which auditory information is retained in uncategorized from (Massaro, 1972). Indeed, it is difficult to see how a store with such properties could be useful. We would have to suppose that information is initially categorized at the incoming level, then translated into uncategorized form for retention in the "preperceptual" store, and finally translated back into the form in which it had first been categorized. No mechanism has been suggested whereby the information that has been lost can be retrieved for recategorization. The concept of a memory array that results as a direct projection from the sensory array, preserving the original form of stimulus categorization, does not run into such difficulties.

Retention of Temporal or Order Information

A memory system must be capable of retaining information concerning not only *what* event had occurred, but also *when* the event had occurred. I conjectured (Deutsch, 1972a) that pitch information is retained both along a pitch continuum and also along a temporal or order continuum, resulting in a distribution such as the one shown in Figure 6-3. It was further conjectured that as time proceeds, this memory distribution spreads in both directions, but particularly along the temporal continuum. Depending on the stimulus conditions, and the task required of the subject, such a spread can lead either to increased errors or to enhanced performance in pitch-recognition judgment.

First, suppose that subjects are required to determine whether two test tones are the same or different in pitch, when these are separated by a sequence of interpolated tones. Then, in conditions where the test tones differ, the interpolation of a tone that is of the same pitch as the second test tone should lead to errors of misrecognition. In other words, due to the spread of the memory distribution along the temporal continuum, the subject should recognize correctly that a tone of the same pitch as the second test tone had occurred, but should be uncertain *when* it had occurred, and so should sometimes conclude erroneously that it had been the first test tone. This effect should be greater when the critical interpolated tone is placed early in the interpolated sequence rather than late. Such findings have indeed been obtained (Deutsch, 1975b).

A second prediction arises from the hypothesized loss of temporal or order information. Suppose that errors were plotted as a function of the pitch relationship between the first test tone and the critical interpolated tone, and that the pitch difference between the two test tones was also varied. Then in sequences where the critical interpolated tone and the second test tone are placed on the same side of the pitch continuum relative to the first test tone, the peak of errors should occur where the critical interpolated tone and the second tone are identical in pitch. In other words, a shift in the pitch of the second test tone, when the pitch of the first test tone is held constant, should result in a parallel shift in the peak of errors produced by the critical interpolated tone. This result has also been obtained (Deutsch, 1975b).

The spread of a memory distribution along a temporal or order continuum may also be expected to give rise to memory enhancement, or consolidation. Suppose that a test tone is presented, followed later by a tone of identical pitch, such that the distributions

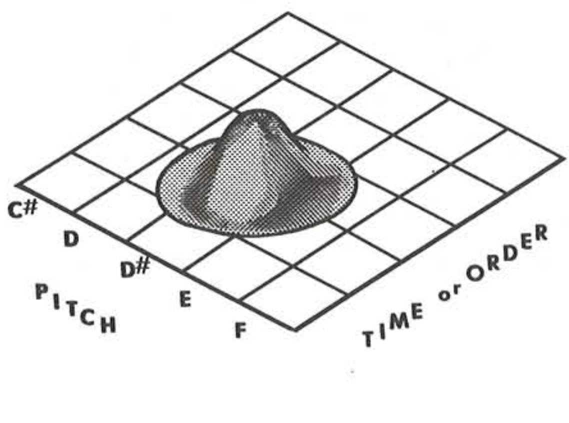

FIGURE 6-3. Hypothesized distribution underlying memory for the pitch of a tone. (From D. Deutsch, Effect of repetition of standard and comparison tones on recognition memory for pitch. *Journal of Experimental Psychology*, 1972, *93*, 156–162. Copyright 1972 by the American Psychological Association. Adapted by permission.)

underlying memory for these two tones overlap along the temporal continuum. The overlapping portions of these distributions should then sum, resulting in a stronger memory trace for the pitch of the test tone. This should, in turn, lead to enhanced recognition performance (Deutsch, 1972a).

An experiment was performed to test this prediction (Deutsch, 1975a). Subjects made pitch-comparison judgments when the tones to be compared were separated by a retention interval during which a sequence of six extra tones was interpolated. In one condition, a tone of the same pitch as the first test tone was included in the second serial position of the interpolated sequence. In another condition, such a tone was included in the fifth serial position. In a third condition, no such tone was included. The repeated tone was found to give rise to enhanced recognition performance at both serial positions. However, this effect was substantially and significantly greater when the repeated tone was placed early in the interpolated sequence rather than late. This is as expected from the hypothesis of a spread of the memory distributions along a temporal or order continuum, since the closer the repeated tone is to the test tone, the greater should be the overlap of their memory distributions.

Organization of Memory for Pitch Relationships

We may conjecture that the form of organization that exists in the case of memory for first-order attributes exists in the case of memory for higher-order attributes also. As an example, let us consider memory for pitch relationships. When two tones are presented simultaneously or in temporal succession, there results the perception of a musical interval. Further, when the fundamental frequencies of two tone pairs are related by the same ratio, these intervals are of the same apparent size (Deutsch, 1969). We may then hypothesize that there exists a memory continuum whose elements are activated by the presentation of pairs of tones. Tone pairs that stand in the same ratio project onto the same point along this continuum; tone pairs standing in adjacent ratios project onto adjacent points; and so on. A monotonic continuum of interval size is thus formed. We may further conjecture that interactions occur along this continuum that are analogous to those found in the system underlying memory for absolute pitch values.

An experiment was performed to test this hypothesis (Deutsch, 1978). Subjects compared the pitches of two test tones when these were both accompanied by tones of lower pitch. The test tones either were identical in pitch or differed by a semitone. However, the tone accompanying the first test tone was always identical in pitch to the tone accompanying the second test tone. So when the test tones were identical, the intervals formed by the test tone combinations were also identical. Further, when the test tones differed, the intervals formed by the test tone combinations also differed.

The test tone combinations were separated by a retention interval during which six extra tones were interpolated. The tones in the second and fourth serial positions of the interpolated sequence were also accompanied by tones of lower pitch. When the intervals formed by the interpolated combinations were identical in size to the interval formed by the first test tone combination, errors were fewer than when the sizes of the intervals formed by the interpolated combinations were chosen at random. Further, when the intervals formed by the interpolated combinations differed in size by one semitone from the interval formed by the first test tone combination, errors were more numerous than when the sizes of the intervals formed by the interpolated combinations were chosen at random.

This experiment demonstrates that effects which are analogous to those found in the system that retains absolute pitch values exist in the system retaining pitch abstractions also. These effects are memory enhancement through repetition, and similarity-based interference in the same relative frequency range.

Interactions between Outputs of Two Memory Systems

Finally, we may inquire how the outputs of two memory systems interact in producing recognition judgments. When comparisons are made between stimuli that vary along one (relevant) dimension, how are these affected by simultaneously varying the stimuli along a different (irrelevant) dimension?

This question was addressed by considering the influence of relational context on judgments concerning the absolute pitches of two test tones. In one experiment (Deutsch & Roll, 1974), subjects compared the pitches of two tones when these were both accompanied by tones of lower pitch. The test tone combinations were separated by a retention interval during which a sequence of extra tones was interpolated. In some conditions, the harmonic intervals formed by the test tone combinations were identical, and in others they differed; these patterns of relationship were present both when the test tones were identical and also when these differed. A strong effect of harmonic context was found. When the pitches of the test tones were identical, but when these were placed in different harmonic contexts, there resulted an increased tendency to judge them as different. Also, when the pitches of the test tones differed, but when these were placed in the identical harmonic context, there was an increased tendency to judge them as identical. In further study (Deutsch, 1982), the effect of melodic context was examined. Here, subjects compared the pitches of two test tones when these were each preceded by tones of lower pitch. Again, the test tone combinations were separated by a retention interval during which a sequence of extra tones was interpolated. A strong effect of melodic context was demonstrated, which was analogous to that found for harmonic context.

Conclusion

An important goal of neuropsychology is to explain behavior in terms of its neurophysiological and neuroanatomical substrates. In attempting to reach this goal, it is useful to seek out paradigms in which patterns of behavior are produced that can be most directly explained in terms of known physiological mechanisms. In the case of memory, one approach is dissect out specific dimensions of representation by behavioral means. Interactions between elements along such dimensions can then be studied, together with interactions between outputs of different dimensions.

This chapter has presented findings which indicate that the above approach is a particularly useful one. Where single dimensions are concerned, findings indicate that memory elements interact in ways analogous to lateral inhibitory interactions that have been studied at the physiological level in sensory systems. This leads us to conjecture that other effects described here—such as memory enhancement through repetition, and loss of temporal or order information—can also be explained relatively directly in terms of hypothesized neural mechanisms. At the same time, such findings appear as examples of memory phenomena that are commonly obtained in a wide variety of situations. These are, for instance, similarity-based interference, consolidation through repetition, and loss of memory for when events had occurred. Such phenomena have generally been studied in situations where multiple memory representations must have been involved, and so where the physiological correlates must have been highly complex. The present findings therefore provide a link between cognitive studies of human memory on the one hand, and studies of relatively simple physiological mechanisms on the other.

ACKNOWLEDGMENT

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