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ABSTRACT

Nine subjects, 5 of whom claimed absolute pitch (AP) ability were instructed to rapidly strike notes on the piano to match randomized tape-recorded piano notes. Stimulus set sizes were 64, 16, or 4 consecutive semitones, or 7 diatonic notes of a designated octave. A control task involved motor movements to notes announced in advance. Accuracy, measured on the basis of deviations of responses from targets, significantly differentiated AP from NAP (non-AP) subjects at all set sizes except the control task. For both groups, accuracy increased as set size decreased. Decision times--that part of total response time before a movement to the response note began--decreased as set size decreased, but did not differentiate AP and NAP subjects. The results are discussed in terms of a two-factor theory of AP ability whereby NAP subjects use only relative tone height as the basis of judgment, but AP subjects also use standards of tone chroma stored in long-term memory. The abnormally high channel capacities and rates of information gain for AP subjects are based on the transmission of information in two channels, whereas NAP subjects transmit information in only one channel. (Author/MV)

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SPEED AND ACCURACY OF ABSOLUTE PITCH JUDGMENTS:

SOME LATTER-DAY RESULTS

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Abstract

Nine subjects, 5 of whom claimed absolute pitch (AP) ability (4 from childhood, 1 by self-training) were given a pitch judgment task in which they had to strike notes on the piano as rapidly as possible to match randomized tape-recorded piano notes. Stimulus set sizes were 64, 16, or 4 consecutive semitones, or 7 diatonic notes of a designated octave. A control task involved motor movements to notes announced in advance, with the effect that set size was 1. Accuracy, measured on the basis of deviations of responses from targets, significantly differentiated AP from NAP (non-AP) subjects at all set sizes except the control task. For both groups, accuracy increased as set size decreased. Decision times, measured as that part of total response time before a movement to the response note began, decreased as set size decreased, but did not differentiate AP and NAP subjects. The performance of the trained AP subject was not distinguishable from that of the remaining AP subjects either in accuracy or decision time. Results are discussed in terms of a two-factor theory of AP ability whereby NAP subjects use only relative tone height as the basis of judgment but AP subjects also use standards of tone chroma stored in long-term memory. The abnormally high channel capacities and rates of information gain for AP subjects are interpreted on the basis of transmission of information in two channels, whereas NAP subjects transmit information in only one channel.

SPEED AND ACCURACY OF ABSOLUTE PITCH JUDGMENTS:

SOME LATTER-DAY RESULTS

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The phenomenon of "absolute pitch" (AP), whereby some individuals are able, without use of a reference tone, to identify or produce tones of specified frequencies or scale names with more than usual accuracy, has been described and discussed by psychologists, musicians, and acousticians for more than a century (Abraham, 1901; Bachem, 1937, 1955; Neu, 1947; Revész, 1953; Seashore, 1919; Siegel, 1972; Slonimsky, 1930; Stumpf, 1883; von Kries, 1892; Ward, 1963a, 1963b; Weinert, 1929; Wynn, 1973), but there are as yet no definitive answers as to whether pitch judgment ability is a continuous or a discontinuous trait, to what extent AP is innate, acquired, or improvable by training, and through what perceptual and/or neurological mechanisms it operates.

The present paper, which is a report of pitch identification tests conducted on nine subjects (five of whom claimed AP ability), takes no final position on any of the major questions stated above. It is intended only to offer data that are more adequately controlled and reported than was the case in most of the earlier investigations, and to suggest answers to certain methodological and theoretical questions about AP ability, namely, (1) how pitch judgment ability can best be measured and characterized, (2) whether superior degrees of pitch judgment ability imply a greater-than-normal channel capacity for the processing of information, and (3) what effect the range of pitch

[1]This work was done, save for some final data analyses, while the author was Senior Research Psychologist at Educational Testing Service. Thanks go to Mr. William Libby, then a research assistant at ETS, for help in developing the instrumentation and procedures, and to the subjects who volunteered their services. I am indebted to Roy Freedle of Educational Testing Service and to Thomas S. Wallsten of the University of North Carolina for helpful comments on an earlier draft of this article. The work was supported by general research funds of Educational Testing Service.

stimuli has on the speed of AP judgments. As an incidental "bonus," it contains data on the performance of one subject who claimed to have acquired AP ability through intensive self-training, and thus may be of some pertinence to the question of the improvability of AP judgments.

Also, as it happens, the investigator himself claims AP ability from early childhood and served as one of the subjects. While this implies some risk of a loss of objectivity, it may represent a considerable advantage in that the investigator is thereby better able to interpret the results. Bachem (1950) complained that many of the investigators of AP did not possess AP and thus failed to understand the phenomenon. Stanaway, Morley, and Anstis (1970) remark that "[M]any of the published studies of AP have been of little value because neither experimenter nor subjects possessed AP."

The Measurement of AP Judgment Ability

Various procedures, reviewed by Ward (1963a, 1963b), have been employed to measure AP ability. One of the most popular has been the categorization task, in which the subject is required to identify or categorize a series of pitch stimuli in terms of their names on the musical scale or in terms of preassigned numbers or other designations. Often the results have been expressed simply in terms of proportions of correct responses, or in terms of average absolute error in semitones (semits). Another type of task uses the method of constant stimuli, in which graded stimuli are to be judged as either higher or lower than, or the same as, a designated pitch. Then there is the method of adjustment, where the subject attempts to adjust a tone generator, a violin string, or other sound-generating device to match a designated pitch, and the method of production, where the subject is asked to sing or hum a designated note. These latter methods lend themselves

readily to measurements in terms of average algebraic or absolute error, an error being defined as the amount of deviation of the response from the target, measured in Hz or (preferably) in semits or cents.

Generally, the errors observed over a number of stimulus presentations tend to be distributed normally, either around zero or some other value. What seems not to have been explicitly pointed out previously is that this form of distribution implies a Thurstone-type discriminal process whereby a stimulus is perceived as falling within a region of a subjective continuum whose extent can be measured in terms of a standard deviation. Further analysis suggests that this discriminal process is only one component of the total error variance--a component that we may call the <u>perceptual dispersion</u> component. In an ideal case, assume that this dispersion is the same, for a given individual, for any region of the subjective continuum, even though the dispersion may diminish or disappear at the extremes of the normal musical scale (Bachem, 1948), but that it varies reliably over individuals. Two other major components of the total error variance are the <u>scale dispersion</u> and the <u>response dispersion</u> components. With regard to the former of these, assume that the subjective continuum itself has some degree of variation in the sense that, subject to such influences as recent past experiences (e.g., listening to music played at a certain pitch standard) or the physiological state of the individual (Wynn, 1972), it exhibits small translations up or down with respect to the physical scale, either on different occasions for the same individual, or for different individuals. Variations in pitch standards from a currently accepted international standard (at present, A4 = 440 H2) would contribute to the scale dispersion component. The response dispersion component of error variance arises when the responses that are elicited from the individual, given

presentations of the same stimulus on different occasions, exhibit deviations with respect to the central tendency of the region of the subjective continuum at which they are perceived. Such deviations may be the result of cognitive confusions, motoric errors in response, or the like.

On the assumption that the three components of variance are independent, the variance of observed response errors is the sum of these variances. Ordinarily, it may be difficult to measure the three components separately, but with appropriate experimental controls and methods of analysis this may be possible, at least to a limited extent. For example, in the present experiment the scale dispersion component is reflected in deviations of the mean algebraic error from zero, and the variance due to the response dispersion component is estimated by having subjects strike notes announced in advance, i.e., with no involvement of absolute pitch judgments. In any case, the usual reports of AP judgments in terms of proportions of correct judgments, or in terms of absolute magnitudes of errors, tend to mask the separate components. Also, the notion of a variance of a discriminal process should lay to rest any idea that AP ability can ever be regarded as truly "absolute" in the sense of being completely errorless--a point that was made even by a nonpsychologist, Slonimsky (1930), some years ago.

The magnitudes of these error variances may be influenced by specific experimental procedures and designs. For example, to the extent that the stimulus and response categories in categorization tasks fail to have exact correspondence with the categories of the individual's subjective continuum, the scale and response dispersion components may be inflated, but to the extent that the number of categories is limited, the perceptual dispersion component may appear to be decreased because of end effects and anchoring strategies on the part of the subject (Ward, 1963a). In the method of production, the

response dispersion component may be inflated if the subject is unable reliably to adjust his vocal cords to produce the pitch he intends to produce.

In the present study, a pitch identification task was employed, partly because it lent itself most readily to the investigation of channel capacity and response latency. The study was designed and analyzed, however, in such a way as to make possible some estimates of the separate components of variance.

Both the pilot and the main experiments involved piano notes as stimuli, rather than, say, sinusoidal tones produced by electronic means, and the subjects were all at least reasonably accomplished pianists. There has been frequent comment in the literature (Abraham, 1901; Baird, 1917) to the effect that piano notes seem to be easier to identify than pitches produced by other musical instruments or the human voice, at least by AP subjects who are most experienced with the piano. Ward (1963a) felt that studies of AP using piano notes should be called studies of "absolute piano," although he was not ready to discard such studies completely. In the ordinary usage of the term among musicians, AP ability has to do with the ability to judge the pitch of musical tones, or the tonality ("key signature," in simple cases) of musical passages, regardless of the instruments on which they are played. The writer has the impression that his own AP ability is about equally good regardless of the timbres of notes being judged (although latency of response might be affected); piano notes are in this respect merely representative of all musical notes. This study, therefore, is concerned with AP ability in a real-life, naturalistic sense. While a replication of the study with sinusoidal stimuli might yield some interesting differences, the results might not be directly relevant to AP ability as observed in practice. Actually, several studies (Siegel, 1972; Stanaway, Morley, & Anstis, 1970) have demonstrated high degrees of AP ability using sinusoidal tones.

AP and Channel Capacity

The supposition that human channel capacity in a single sensory modality is limited to about 2.5 bits, as suggested by Miller (1956), Attneave (1959), and Garner (1962), is apparently contradicted by the fact that individuals claiming AP ability can make absolute judgments of many more distinct musical pitches than the five or six implied by the figure of 2.5 bits. In the case of the pitch modality, the low estimate of channel capacity seems to have been based primarily on the work of Pollack (1952, 1953), who found that his subjects were unable to make reliable absolute judgments of more than five equally likely tones (2.3 bits) selected in various ways along the pitch continuum. Pollack made no report that any of his subjects claimed AP ability, and admittedly made no attempt to investigate individual differences. In his discussion of Pollack's findings, Miller (1956) decided to disregard the evidence that "a musically sophisticated person with absolute pitch can identify accurately any one of 50 or 60 different pitches" because he saw no way to explain this superior performance. Earlier, Ward (1953) had cited a case of an AP possessor who could make accurate judgments of over 70 pitches, suggesting that this implied the transmission of over 6 bits of information. Attneave (1959) mentioned unpublished work by Miles Rogers reporting the ability of a symphony orchestra concertmaster to transmit 5.5 bits (equivalent to the accurate absolute judgment of 45 distinct tones), but made no attempt to square this finding with Pollack's results. While Pollack's findings have been amended or criticized in various ways (Fulgosi & Zaja, 1972; Fullard, Snelbecker, & Wolk, 1972; MacRae, 1970), the essential contradiction between the fact of AP ability and the notion of a channel capacity limited to around 3 bits has remained.

One possible resolution has been suggested by Stanaway, Morley, & Anstis (1970), namely, that if the pitch continuum is taken to have two components, tone height and chroma (Bachem, 1937, 1950; Révész, 1913; Shepard, 1964), each of these components may have its own limited channel capacity. Stanaway et al. suggest that even for AP subjects the channel capacity for chroma may be no more than about 3 bits; actually, if AP subjects transmit information about this component perfectly, and if it is assumed that the chroma component contains exactly the 12 tones of the tempered musical scale, this transmission carries $\log_2(12) = 3.585$ bits. The information carried by the tone height component would depend upon the AP subject's ability to identify the octave in which a given pitch lies, and, of course, the number of octaves embraced in the stimulus set. The six or more bits of information assumed to be transmitted by AP judgments in the general case would be the sum of the bits of information carried by tone height and chroma; there is evidence (Levy & Norton, 1972) that under some conditions information from different sensory dimensions is additive (but see Miller, 1956, pp. 87-89 on this point).

While this interpretation may serve to explain the performance of AP subjects, it leaves open the question of whether AP subjects are in some way qualitatively different from subjects not claiming or exhibiting AP ability, as suggested by Bachem (1950). It would seem that an answer to this question might be yielded by data in which the information for the two components of the pitch continuum is computed separately, both for AP and non-AP (NAP) subjects. Such an analysis might have a bearing on the question of whether there are in fact two components in the pitch continuum, a question that has been debated endlessly. For example, Ward (1963a, p. 19) appeared to doubt this, but the kinds of demonstrations offered by Shepard (1964) and Risset (1969) seem

completely convincing to this writer, who would also claim that the distinction between tone height and chroma is patently obvious from his subjective impressions. (It would not be necessary, as Ward seemed to require, that recognition of tone height and chroma be a two-stage process. Furthermore, later on Ward seems to have changed his mind [1970, p. 413].)

Speed of AP Judgments

From the time of the earliest discussions (Stumpf, 1883) it has been noted that pitch judgments made by AP subjects are much faster than those of NAP subjects, who often require at least a few seconds to deliberate about their judgments. It has also been claimed (Whipple, 1903) that even for AP subjects, the correct judgments are faster than the incorrect ones. There are, nevertheless, few studies of the latencies of AP judgments--either for AP or NAP subjects, and those that exist (Abraham, 1901; Baird, 1917; Weinert, 1929) are of limited value either because of primitive technology, limited design, or inadequate reporting. The present study was designed to obtain data on accuracies and latencies of AP judgments as a function of stimulus set size both for AP and NAP subjects, the judgments being obtained under instructions to the subjects to respond as accurately and rapidly as possible. The data will also be pertinent to an assessment of the rate of gain of information in the pitch modality, in terms of what is known as Hick's law (Brainard, Irby, Fitts, & Alluisi, 1962; Bricker, 1955; Briggs, 1972; Hick, 1952; Hyman, 1953; Pachella & Fisher, 1972).

Method

In a pilot experiment in which the writer used himself as a subject, the task was to strike, as rapidly as possible, a note on a piano that would exactly

match a note that was heard struck on another piano by an assistant from computer-generated lists of randomly selected notes. Lists contained notes chosen from sets of 4, 8, 16, or 32 consecutive semitones centered at the approximate middle of the piano keyboard. Under one condition, the subject could use either hand in responding; in a second condition, he had to use his preferred (right) hand only. Although there were striking regularities in the data, their interpretation was clouded by the fact that the response times included an unknown amount of time for the movement required to find and strike the response note. No significant differences in total response time were traceable to the one-hand vs. two-hand conditions, however. The pilot data also suggested that trials must be well separated in time, and that constraints must be put on the randomization of note lists, in order to minimize the possible effects of relative pitch judgments of successive notes that are identical or closely similar (modulo an octave). The main experiment, described below, attempted to capitalize on what was learned in the pilot experiment.

Subjects

There were 9 subjects in all. Four of these, including the writer, claimed to have had AP ability since childhood; they are subsequently designated as EAP (early AP) subjects. They consisted of two males and two females ranging in age from 20 to 60. A fifth subject was P. T. Brady, aged 35, who in a published article (Brady, 1970) claimed to have successfully acquired AP ability through intensive self-training, starting from a state in which he was convinced that he "qualified as an adult without AP" (p. 884); he is here designated as a TAP (trained AP) subject. The remaining four subjects were amateur musicians, all male, aged 22 to 40, who did not claim AP ability; they are here designated as

NAP (non-AP) subjects. All subjects were pianists with at least average degrees of skill--some with excellent skill; other than the writer and Brady, all were volunteers recruited by personal contacts either at Educational Testing Service or in the Princeton (N. J.) community.

Both the author and Brady had established their AP ability by judging one note per day soon after arising (avoiding exposure to musical sounds before making the judgment). The author had his wife strike on the piano, each day, a note from Petran's (1932) list of 50 random notes spanning some 4 octaves in the middle of the piano keyboard; 47 (94%) of his judgments, all made promptly but without a speed requirement, were absolutely correct, while the remainder were errors of one semit. There were no octave errors. This performance may be compared, incidentally, to that of Petran's <u>best</u> subject, who had 37 (74%) correct, 10 errors of one semit, and 3 errors of 2 semits. (The remainder of Petran's music-student subjects had generally much poorer performance.) Brady (1970) reports, for a 57-note randomized list for which he named only the note and not its octave, 37 correct (65%), 18 one-semit errors (31%), and two 2-semit errors (4%).

Whether the remaining AP subjects had "genuine" AP ability in the sense defined by Bachem (1937) can perhaps be judged from their performance in the experiment. Interviews seemed to establish, however, that they did not report experiences that would classify them as "pseudo-AP" or "quasi-AP" subjects according to Bachem's definitions.

Design and Procedure

While being tested, the subject was seated comfortably and in the normal playing position at a grand piano that had been professionally tuned to A4 = 440 Hz, the standard international pitch adopted in London in 1939 (replacing

an old standard of A4 = 435 Hz set in Paris in 1859). The piano was instrumented with microswitch bars ("touchplates") fixed directly in front of the keyboard at four points, namely between the E and F keys of the C2, C3, C4, and C5 octaves. (C4 is "middle C.") Immediately before each trial, the subject was required to place the index finger of his preferred hand (all subjects were right-handed) on the microswitch bar that was at or near the center of the range of notes from which the stimulus notes to be judged were to be chosen. With respect to the keyboard, this meant that the tip of the finger was approximately 1.5 cm below the surface of the keyboard and 3 cm in front of its front edge. Red tabs were affixed to the notes just above and below the range in order to define its boundaries for any given set of trials. Two or three seconds prior to each stimulus note (these intervals being more or less random), the word "Ready" was heard, in earphones worn by the subject, from the tape recording containing the stimuli; the stimulus note was then heard. Presentation was binaural. The subject's task was then to strike, as rapidly as possible, the note on the keyboard that would exactly match, in pitch, the note heard from the tape recording. Since this was a normal piano rather than a "mute" keyboard, the note actually sounded, providing feedback. It may be presumed that all subjects were continually aware of their hits and misses since the sounding of the response note provided an immediate and obvious comparison with the stimulus.

From the tape recording, which contained all instructions and which was identical for all subjects, each subject received a total of 344 trials, divided into 4 blocks of 86 trials each. Each block, however, was divided into 5 subblocks as follows:

(1) 32 trials using stimulus notes selected from a range of 64 consecutive semitones from A1 to C7 (the touchplate used being between E4 and F4, the center of this range);

(2) 16 trials using stimulus notes selected from a range of 16 consecutive semitones from A3 to C5 (touchplate as before);

(3) 8 trials using stimulus notes selected from a range of 4 consecutive semitones from D#4 to F#4 (touchplate as before);

(4) 14 trials using stimulus notes selected from the 7 "white-key" notes within one of 4 octaves, the octaves being those starting at C3, C2, C4, and C5, respectively, over the four blocks, and the touchplate being between the E and F keys of the given octave; and

(5) 16 trials using stimulus notes selected from the 64-note range from A1 to C7, as in subblock 1, but with the names of the notes announced in advance. In these trials the touchplate used was that also used in subblock (1).

Between blocks, rest periods of 15 to 30 minutes were taken; the subblocks were separated only by the time required to give any new instructions and adjust the equipment when necessary. The interval between the stimuli of successive trials was approximately 15 seconds; this time was regarded as long enough to eliminate most of the effects of immediate memory for pitch (Bachem, 1954). The entire experimental session lasted about 2.5 hours.

Subblocks 1, 2, 3, and 4 required absolute pitch judgments transmitting 6, 4, 2, and 2.8 bits of stimulus information per trial, respectively. Subblock 5 was included to obtain reaction times to notes announced in advance, and may be considered to involve zero bits of information per trial. Subblock 4 was included in each block to replicate an experiment reported by Abraham (1901).

No practice or warm-up preceded the trials; in the first block, the instructions applicable to each subblock were given immediately preceding the trials of that subblock and not subsequently repeated. In the course of the general instructions for the experiment, the note C3 was sounded and identified, but at least a minute intervened between this and the start of the trials in the first block.

The stimuli were recorded on tape from the same piano that was used in the experimental sessions, and played back during the sessions using the same recording machine (a Tandberg Model 74B, at a tape speed of 9.5 cm/sec) used in recording the stimuli. Variations in tape speed were minimal and seemed to present no problem whereby stimuli would be "out of tune" with the piano. For each subblock, the stimuli had been selected by a computer-programmed pseudo-random process designed so that in each range, each possible stimulus note would be represented equally often over the 4 blocks; in subblocks 1 (the 64-note range) and 2 (the 16-note range), the process was constrained so that no two successive stimuli would be the same or within 2 semits at the given octave or at any other octave in the range. For example, if a stimulus note was F4, the next stimulus could not be D#, E, F, F#, or G at this or any other octave. In subblocks 3 and 4 the randomization was constrained so that no two successive stimuli would be the same. Subjects were not informed of these constraints, introduced in order to minimize or reduce relative pitch effects, but there is little reason to believe that their judgments would have been influenced even if they had been informed of them. (The writer, of course, had knowledge of them, but has no memory of any awareness or influence of this knowledge while serving as a subject.)

The entire experimental session for each subject was recorded on a second tape-recorder. Use of signals recorded on two channels of the tape, together

with use of a Hunter digital timer both during the experiment and afterwards, made it possible to obtain measurements of two time intervals for each trial: (1) the time from the onset of the stimulus note to the opening of the circuit in the microswitch that occurred when the subject's finger left the touchplate, and (2) the time from the opening of the microswitch circuit to the onset of the response note as recorded on the tape. For convenience, the first of these intervals will be called the <u>decision time</u> (DT), and the second, <u>movement time</u> (MT). DT and MT are analogous, respectively, to the RT (reaction time) and MT (movement time) measured in an experiment on movement accuracy reported by Fitts and Peterson (1964), but they are <u>not</u> analogous, it may be noted, to the reaction and motor times as measured in an experiment by Danev, deWinter, and Wartna (1971). The sum of DT and MT constitutes <u>total time</u> (TT).

Listening to the tape for each subject after the experiment was completed, the author made a record of the response note given to each stimulus note; in this process he had access to the piano so that there would be no doubt as to the accuracy of the scoring.

Results

Occasional problems in the conduct of the experiment and in its instrumentation resulted in a slight loss of data, ranging from 0.9% to 6.4% over subjects. The analysis presented here is based on the 3014 responses (97.3% of a possible total of 3096) that are regarded as valid and measured with accuracy within the limits of the instrumentation.

Accuracy of Judgments

<u>Trends over blocks</u>. Since the 4 blocks could be regarded as replicates differing only in their pseudorandom selections of stimulus notes, the accuracy

data from these blocks (pooled proportions correct plotted in Figure 1 separately for AP and NAP subjects) were examined for any indication of significant practice, warm-up, or fatigue effects. The arcsin-transformed

Insert Figure 1 about here

proportions of strictly correct responses (i.e., responses exactly matching stimulus notes, with no allowance for octave errors) for each block and each subject were treated as the dependent variable in a 4 x 9 repeated-measures ANOVA for each subblock. The results, shown in Table 1, indicate that while Subject was a significant ($p < .01$) variable in all subblocks except that

Insert Table 1 about here

for the 1-note range (where the task was purely motoric), Block was a significant variable ($p < .05$) only for the 64- and 7-note ranges. There was some indication of improvement from Block 1 to Block 2, and decline from Block 3 to Block 4, but these trends were not particularly striking or consistent. Also, AP and NAP subjects did not appear to differ in trends over blocks, although of course they differed strikingly in overall accuracy of performance. Since the Block 1 data represent the most freshly performed judgments (thus with the least intrusion of relative pitch effects), it was decided to retain them in the data set and to pool the data from all blocks for subsequent analyses.

Distributions of errors. Each response was scored in terms of the algebraic number of semits that it deviated from the stimulus note, positive errors being those occurring when the response note was higher in pitch, and negative errors when the response was lower. A zero error was recorded for a

correct response. Although there were minor differences among the error distributions of the EAP and TAP subjects, as well as among those of the NAP subjects, the major differences of interest are those revealed when the AP (EAP and TAP) distributions are pooled and compared with the pooled error distributions for the NAP subjects. The resulting error distributions are shown as histograms, separately for the 5 conditions (i.e., 5 subblocks, pooled over block), in Figure 2. As appropriate chi-square tests confirm,

Insert Figure 2 about here

the error distributions of the AP subjects are obviously different from those of the NAP subjects, except for the 1-note range (where the task did not involve absolute pitch judgments).

In the 64-note condition, 65.3% of the responses of the AP subjects have zero error, as compared to 9.6% of those of the NAP subjects. The remaining responses of the AP subjects have errors close to zero, except for small proportions occurring in the neighborhood of +12 (5.9%) and -12 (1.9%) which appear as distinct clusters in the histogram. These are the familiar "octave errors" reported in the literature of AP ability (Bachem, 1937; Stumpf, 1883); they represent responses where the subject perceives (or misperceives) the "chroma" of a note but places it in the wrong octave. Révész (1953) argues that an error distribution with clusters of octave errors is strong evidence for the presence of superior AP ability, but Ward (1963a) suggests that octave errors may be an artifact of the use of complex tones such as notes struck on the piano. In any event, there is little indication of clustering around octave errors in the pooled error distribution for the 64-note data from the NAP subjects (clustering does not occur, either, in the individual error

distributions for these subjects), and in fact this distribution shows a very wide dispersion, over about three octaves.

The clustering of octave errors occurs only in the data for the 64-note range condition. The 16-note range comprised only 1 1/3 octaves and thus provided little opportunity for octave errors; each of the other ranges comprised less than an octave (except that the notes given in the 1-note range condition were spread over 5 1/3 octaves). The fact that octave errors occur suggests that separate analyses may be made in terms of octave and chroma errors. In such an analysis, we take errors from -6 to +6 to be pure chroma errors with zero octave error; errors on either side of this range are then transposed, modulo 12, in such a way that they become chroma errors of -6 to +6, with associated octave errors of, for example, -1 for errors in an octave below an error of -6 semits, and +1 for errors in an octave above an error of +6 semits. When this is done for both AP and NAP subjects, the former are found to have 70.8% zero chroma errors under the 64-note condition, as compared to 12.5% for the NAP subjects.

Measures of accuracy. Computations of various statistics can thus be made separately for chroma and octave errors. Table 2 shows detailed results for individual subjects in the 64-note range condition for total, chroma, and octave errors. Table 3 contains results for other note-ranges, but since errors beyond an octave were rare in these ranges even for NAP subjects, the statistics shown are only those for chroma errors; except for four instances (two in the 16-note condition and two in the 1-note condition) these values would be exactly the same as those computed from total error data.

Insert Tables 2 and 3 about here

In both Tables 2 and 3, the columns for subjects are ordered within AP groups by increasing chroma error variance in the 64-note range condition; in general these orderings hold up for the chroma error variances in the other ranges requiring AP judgments. The coefficients of concordance of each measure over the 64-, 16-, 7-, and 4-note ranges are as follows:

Proportion of zero chroma errors ..	.808**
Proportion of zero chroma errors, corrected for white-note bias and guessing (7-note range omitted)	.844**
White-note bias (7-note range omitted)	.478
Mean algebraic chroma errors	.416
S.D. " " "	.821**
Mean absolute chroma errors	.827**
S.D. " " "	.853**

** $p < .01$.

As indicated by the coefficients of concordance, the highest agreement in ranking the subjects' performances over different conditions is attained by using the standard deviation of absolute chroma errors. This measure, however, tends to include scale dispersion, which in turn is measured by the mean algebraic chroma error. While not significant at $\alpha = .05$, the coefficient of concordance for the latter measure indicates some trend for the subjects to be consistent over note-range conditions in judging pitch higher or lower, as the case may be, than the standard of the target. On the other hand, there are few instances in which an individual's mean chroma error shows a significant departure (at $\alpha = .05$) from a hypothesis value of zero, relative to the variance of the errors. These few instances are indicated by asterisks in Tables 2

and 3. In general, then, it may be said that little variance due to scale dispersion is present either for AP or NAP subjects. This probably implies that the subjects' subjective scales are accurately "tuned" to near A4 = 440 Hz; while this may not be so remarkable for the AP subjects, it is somewhat surprising that NAP subjects can judge so accurately, on the average, when given enough opportunities to do so.

From the standpoint of the model of sources of variance stated near the beginning of this paper, the standard deviation of algebraic chroma errors is probably the preferable measure of subjects' performance, since it would reflect mainly perceptual dispersion variance and include only a negligible amount of scale dispersion variance. It also adjusts for octave errors; this adjustment is certainly important to make for AP subjects, and making it for the NAP subject data is desirable for the sake of comparability. This measure provides a highly significant differentiation between AP and NAP subjects for all note-range conditions requiring absolute pitch judgments (see the t-tests in Tables 2 and 3).

The proportions of zero chroma errors also provide excellent differentiation between AP and NAP subjects as shown by t-test, but they are affected by two sources of bias: (1) there are different degrees of chance success in the various note-range conditions, and (2) some subjects had a tendency to make a much higher proportion of "white-note" responses than would be expected by chance. In the 64-note range, there were 38 possible white-note stimuli (59.4%) and 26 possible black-note stimuli (40.6%). Similarly, in the 16-note range, there were 10 possible white-note stimuli (62.5%) and 6 possible black-note stimuli (32.5%). When the error distributions are collapsed to measure only chroma error, there are 7 white notes and 5 black notes within an octave.

Only in the 4-note range were white and black notes equiprobable. Any subject with a high tendency to respond with a white note regardless of the stimulus has a greater probability of success when the stimulus note is a white note.

A procedure was devised to estimate true proportions correct, adjusted for white-note bias and other forms of guessing behavior. Let

$p_c = 1 - q_c$ = the probability of a correct response on the basis of true judgment;

$p_w = 1 - q_w$ = the probability of giving a white note response in the absence of a true judgment;

N_w = the number of white-note stimuli in the stimulus set;

w = the number of different white-note stimuli in the stimulus set;

N_b = the number of black-note stimuli in the stimulus set;

b = the number of different black-note stimuli in the stimulus set;

$N_w + N_b = N$ = the total number of scimuli in the stimulus set;

W_r = the number of white-note responses for a subject;

B_r = the number of black-note responses for a subject;

$W_r + B_r = N$;

W_c = the number of correct white-note responses for a subject;

B_c = the number of correct black-note responses for a subject.

Then we may suppose the following relations to hold in theory:

(1) $W_r = p_c N_w + p_w q_c N$

(2) $B_r = p_c N_b + q_w q_c N$.

That is, the number of white or black responses is equal to those correct by true judgment plus a fraction of the remainder as determined by white-note bias.

(3) $W_c = p_c N_w + p_w q_c N_w / w$

(4) $B_c = p_c N_b + q_w q_c N_b / b$.

That is, the number of correct white or black responses is equal to those correct by true judgment plus a fraction of the remaining white or black stimuli as determined by both white-note bias and chance success.

Since we have four equations in only two unknowns, we may estimate the unknowns separately for white-note and black-note data, and take weighted averages of the parameters estimated from the two sources. Thus, solving equations (1) and (3) for p_c and p_w, we have

(5) $p_c = [W_r - N(W_r - W_c)/(N - N_w/w)]/N_w$

(6) $p_w = (W_r - W_c)/[(N - N_w/w)q_c]$.

The solutions for equations (2) and (4) are similar, except that the analogue of equation (6) gives q_w. While the respective values of p_c and p_w resulting from the two solutions can be identical, they are in practice usually slightly different. The values given in Tables 2 and 3 for p_c (proportion zero errors, corrected) and p_w (white-note bias) are averages computed by weighting the values from the two solutions proportionately to the number of white- and black-note stimuli (N_w and N_b). In several cases the values of p_w are either indeterminate (when $p_c = 1$) or slightly greater than unity, apparently because of some chance departure of the data from the model.

It is to be noted that the corrected proportions of correct responses give a slightly more consistent ranking of the subjects over the 64-, 16-, and 4-note conditions than the raw proportions correct, although the corrected proportions provide no better differentiation between AP and NAP subjects. In any case, it is believed that the corrected proportions yield a more accurate impression of success rates over the three conditions; for NAP subjects they descend to near zero for the 64-note range condition. The corrected proportions are plotted

as a function of stimulus information in Figure 3, where it is seen that success rates are a decreasing function of stimulus information.

Insert Figure 3 about here

Throughout this discussion, the data for the TAP subject have been considered along with the data for the EAP subjects to constitute a pool of AP subject data, since the TAP subject's data are such as to make it untenable to regard him as other than a subject drawn from a population of EAP subjects. If we grant this subject's own claim (Brady, 1970) that he did not have AP ability before starting to train himself in it, it appears that AP ability can indeed be trained to a level of accuracy exhibited by persons claiming AP ability from early childhood. The only hint that the TAP subject may be different from the EAP subjects is his perfect performance in the 7-note range condition, where only white-note stimuli were presented (i.e., the notes in the scale of C). This possibly results from the fact that Brady trained himself with the scale of C and insists that his AP ability is anchored relative to this scale (but see Corliss, 1973). On the other hand, Brady performed in a manner quite similar to other AP subjects even in the 64-note range, where all notes (both white notes and black notes) were equiprobable over more than 5 octaves of the keyboard.

Brady was also one of the two subjects who made no errors in the motoric task in the 1-note range condition. Small amounts of error (including two octave errors in the whole data set) were made by the remaining subjects, but as expected, AP and NAP subjects were not significantly differentiated in this respect. The data for the 1-note range condition may be regarded as providing estimates of the amount of response dispersion variance included in error

variances in the other conditions, particularly that for the 64-note range since a comparable range of stimulus notes was involved.

Accuracy as a function of tone chroma. Several writers (Abraham, 1901; Baird, 1917; Weinert, 1929) have discussed the possibility that notes of the musical scale vary in their ease of recognition by AP subjects. They, and others, have also observed that white notes seem to be easier to recognize than black notes. There appear to be no relevant data in the literature that are reported with appropriate statistical tests, however. In the present study, repeated-measures ANOVA's were performed on arcsin-transformed proportions of correct responses for different notes of the musical scale, or groups thereof. The five AP subjects were regarded as repeated measures of the notes. Because the total numbers of responses per note were relatively small, data were pooled over the 64- and 16-note conditions; they were also pooled over octaves. The overall test of variation in proportions correct over the 12 notes of the scale was not significant ($F_{11, 44} = 1.21$, $p > .05$), and neither were tests for variation among white notes ($F_{6, 24} = 0.96$, n.s.) and among black notes ($F_{4, 16} = 0.69$, n.s.). Any variation in proportions correct over different notes could therefore be said to be due to random error and the idiosyncrasies of particular subjects. Thus, the fact that C received the highest proportion of correct responses both in the 64-note and the 16-note conditions cannot be taken as being of any particular significance, at least from the present experiment. On the other hand, there was a highly significant difference ($F_{1, 4} = 199.02$, $p < .001$) between the proportion correct for white notes (.807) and that for black notes (.700), but this difference can probably for the most part be ascribed to the fact that for most subjects, in both conditions, the white-note bias (p_w) was greater than .5 (see Tables 2 and 3).

Accuracy as a function of tone height. It has been suggested in the literature of AP ability (Stumpf, 1883; Ward, 1963a) that notes in the middle of the keyboard are easier to recognize than notes at the extremes. Pooled data from the five AP subjects in the present experiment show nonsignificant variation over five approximately equal note ranges in the 64-note condition ($F_{4, 16} = 0.63$). Also, in comparing data from the four blocks in the 7-note condition, where a different octave was used in each block, the variation was only barely significant at $\alpha = .05$ ($F_{3, 12} = 3.47$). But this latter variation is confounded with possible practice effects over the blocks; the proportions correct for octaves C2, C3, C4, and C5 were .914, .884, 1.000, and .986 respectively, with no obvious trend appearing. Furthermore, the use of arcsin transformations with extreme proportions involving small N's makes this test of significance of dubious value.

Information Transmitted

Response error data can be translated into measures of information transmitted. In studies of information transmission, this is usually done by the procedure suggested by Garner and Hake (1951) in which the information transmitted is a function of the probabilities in the response categories conditional upon the stimulus categories. Since musical pitch is a continuum, this procedure seemed inadequate for the present data since with the Garner and Hake computations a maximum amount of information would be found to be transmitted even if all the responses were incorrect (even far from their targets), just as long as the responses were perfectly predictable from the stimuli. Therefore, a procedure was devised for indexing the amount of information transmitted by each response relative to its deviation from the correct stimulus category.

This procedure provided for separate estimations of chroma and octave information, as well as total information.

Consider, for example, information transmitted by responses in the 64-note condition. A strictly correct response would transmit $\log_2 (64) = 6$ bits of total information. But this could be regarded as being composed of both chroma information and octave information. Since under the conditions of the present experiment there were 12 separate response categories in an octave, a correct response would transmit $\log_2 (12) = 3.585$ bits of chroma information, and since there are 5.33 octaves in the 64-note range, it would transmit $\log_2 (5.33) = 2.415$ bits of octave information.

A response with an error of one semit in either direction has the effect of carrying the amount of information transmitted if the 12 semitones of an octave were divided into 4 sets of 3 semitones; that is, the response "correctly" assigns a stimulus to one of these 4 sets. Similarly, a response with an error of 2 semits from the stimulus assigns the stimulus to one of 2.4 sets of 5 semitones each. Generalizing for any given amount of response error (e being the absolute magnitude of the error in semits), we find the amount of chroma information (I_c) as

$$I_c = \log_2 [12/(2e + 1)] .$$

The rationale for octave information (I_o) is similar; this is given by the formula

$$I_o = \log_2 [5.33/(2o + 1)] ,$$

where o is the absolute value of the error in octaves, or more generally (for other note-range conditions)

$$I_o = \log_2 [n_o/(2o + 1)] ,$$

where n_o = n/12 = the number of octaves in the range (n being the number of semitones in the range). Regardless of the range, $I_c + I_o = I_t$. For note ranges less than 12, this results in negative octave information, but this seems permissible, for the sake of generality, to reflect the fact that in such ranges octave information is automatically given to the subject by the experimental setting, and thus no decisions about it are necessary.

It is also the case in the above calculations that a response error of $\pm$ 6 semits results in negative chroma information, namely, -.116, but this is unavoidable since such an error is at the intersection of octaves.

Each response in the present data set was scored for I_c, I_o, and I_t. The summarized results for the 64-, 16-, 7-, and 4-note range conditions are given in Table 4. Computations of I_c, I_o, and I_t were made for the 7-note

Insert Table 4 about here

range condition with errors counted in semits (as in other conditions) but on the assumption that since there were only 7 response notes, the range comprised 7/12 of an octave. Thus a response with an absolute total error of 0 to 6 was scored as transmitting $I_o = -.778$; the few errors outside this range (all committed by one NAP subject) received $I_o = -2.36 = \log_2 [7/(3 \cdot 12)]$. For all conditions, it was necessary to compute the mean information transmitted if all possible responses to each stimulus note were equiprobable; these values are recorded as the "chance" values in the table, along with the maximum possible values expected (according to the methods of computation used) if all responses were correct. Along with the means and estimated S.D.'s, values are given for the proportion of possible information transmitted whereby the data are scaled in terms of their proportional distance from

chance along the scale from chance to maximum. The table also gives values of t for the comparison of means for AP and NAP subjects. (Since the proportions of possible information transmitted are linear transforms of values of I_c, I_o, or I_t, the values of t apply also to them.) In the 4-note range, no data are given for octave and total information since there were no octave errors in this condition; values of I_t may be found by subtracting 1.585 from values of I_c.

In each note-range condition, AP and NAP subjects are significantly differentiated ($p < .01$) in terms of both chroma and total information. They are significantly differentiated in octave information only in the 64-note condition, but the NAP subjects still transmit a fairly high proportion of octave information in this condition (.710, on the average), as compared to the proportion (.908) for AP subjects. That is, they are fairly good at identifying the octave in which a stimulus note lies, but poor at identifying the particular note in an octave.

Data for individual subjects are plotted in Figures 4 and 5. AP subjects transmit near the maximum possible total information in all note-range conditions, although several of them falter slightly in the 64-note condition.

Insert Figure 4 about here

The best AP subject transmitted, on the average, 5.71 bits of total information in this latter condition, 93.3% of the possible 6 bits. Even the poorest AP subject transmitted 4.86 bits (73.8% of possible). NAP subjects, on the other hand, tended to transmit a constant fraction of the possible total information, roughly 55%. The slightly better performance for the 4-note range may possibly be accounted for by an end effect whereby errors tended to regress toward the

middle of the range. In any case, the data for the NAP subjects (and even more so for the AP subjects) seem to contradict the findings of Pollack (1952) in at least two respects: first, at 2 bits of stimulus information, the expected amount of information transmitted is not necessarily 2 bits; second, maximum total information does not have a limit of around 2.5 bits. With 6 bits of stimulus information, the average NAP subject transmitted 3.29 bits, while the average AP subject transmitted 5.32 bits. Also, there is no evidence of a decline of information transmitted with increasing stimulus information such as MacRae (1970) found in reanalyzing Pollack's data.

As suggested previously, pitch may be a two-dimensional continuum containing both chroma and octave information. It is thus possible that the high estimates of channel capacity for AP subjects should be viewed as sums of capacity values for these two dimensions. First, note that the values of I_o do not differ much between AP and NAP subjects. In the 64-note condition, AP subjects transmitted 2.29 bits on the average, and NAP subjects transmitted 2.02 bits, compared with the maximum possible of 2.415. From the data of the present experiment, it is possible only to speculate as to what amount of octave information could have been transmitted if a larger number of octaves had been embraced in the stimulus sets. As it happens, the 2.35 bits of octave information transmitted by the best AP subject for the 64-note condition is close to the claimed channel capacity of 2.5 bits suggested by Miller (1956) and others.

The case is different, however, for chroma information, individual data for which are to be seen in Figure 5. AP subjects achieved at or near a

Insert Figure 5 about here

maximum of 3.585 bits of chroma information in the 4-, 7-, and 16-note conditions,

and the best of them transmitted nearly all of that in the 64-note condition. It must be remembered that the task involved a set for speed; at least some of the failure to transmit maximum information may be ascribed to this, although AP subjects report that they generally have an immediate impression as to the chroma of a note and feel that that impression is "correct" even though it may be later invalidated.

Although NAP subjects transmit significantly less chroma information than AP subjects do under all conditions, in the 4-note condition they appear to be transmitting as much information, about 3 bits, as the AP subjects do in the 64-note condition. Some doubt, however, may be raised as to whether any subject (even an AP subject) is actually transmitting as much as 3 bits of information in the 4-note condition, since maximum <u>total</u> information is only 2 bits and octave information is consequently negative. The measures of chroma information at the 4- and 7-note conditions may be an artifact of the method of scoring.

The fact remains, however, that all AP subjects were found to transmit well over 2.5 bits of chroma information, usually from 3.0 to 3.4 bits, under the 64-note condition. This seems to be in clear contradiction to estimates of channel capacity derived from the findings of Pollack and others. Only Fulgosi and Zaja (1972) and Fullard, Snelbecker, and Wolk (1972) appear to have obtained channel capacity estimates as high as around 3 bits for the judgment of pitches by unselected subjects, but their stimuli were more widely spaced than semitones, and their experimental settings were quite different from that employed in the present study. Further, their estimates were for total information, not simply chroma information.

Latencies of Responses

Data treatment. Examination of each subject's distributions of total response times (TT's), decision times (DT's), and movement times (MT's) over blocks for the various note-range conditions disclosed considerable tendency toward positive skewness and lack of homogeneity of variance. Response times were converted to their reciprocals for many types of analysis reported here; this process tended to normalize the distributions and make the variances more homogeneous across subjects. Where necessary, means of reciprocals are back-transformed to values of response times in seconds or msec, values which are in effect the harmonic means of the original response times. A rationale for the use of the reciprocal transforms of response times is that the reciprocals are measures of speed or rate of response.

Since the TT for each response is a sum of its DT and MT, and since MT is substantially correlated with the absolute distance of the response note from the starting position (the "touchplate" on which the subject's finger rested prior to the response), the main analyses are in terms of (the reciprocal of) DT. As is shown below, DT is significantly affected by note-range condition and is in general independent of note distance. This evidence suggests that DT's can indeed be regarded as "decision times," since it appears (as might logically be expected) that the subject's finger does not leave the touchplate until the subject has made at least a partial decision as to where on the keyboard the response will be made. For some subjects, this decision appears to be practically complete within the DT phase of the response; for others, a part of the MT is occupied with refining the decision or perhaps with the visuo-perceptual and motoric planning aspects of finding and striking the response note. Observations of subjects during the experimental sessions suggest that

it is mainly the latter: occasionally subjects would appear to move the finger rapidly to a particular region of the keyboard and then "circle" that region (like a bee or an airplane) before finally landing on a particular note. This sort of behavior occurred, particularly among the less skilled pianists, even in the 1-note condition when the note to be struck had already been announced in advance; it resulted in quite deviant MT values.

Latencies for correct and incorrect responses. Analysis of the data presented the problem of whether the results should be reported for all responses or only for correct responses. Mean reciprocals of DT's for correct responses were compared with those for incorrect responses for each subject in each of the 4-note range conditions involving absolute judgment. Some of these comparisons could not be made because there were no incorrect responses. Of 32 (out of 36 possible) comparisons that could be made, three were significant (by two-tailed t-test) at $\alpha = .01$, and two others at only $\alpha = .05$. All five of these significant differences indicated correct responses as faster than incorrect ones; of the remaining, nonsignificant differences, 19 indicated faster correct responses and eight indicated faster incorrect responses. There was little consistency in the results either by subjects or by note-range conditions, except that there was only one instance of faster mean incorrect response for AP subjects. It may be concluded that the data give some weak confirmation to Whipple's (1903) observation that correct responses were faster than incorrect ones in an AP subject.

For analyses using both AP and NAP subjects, times for all responses are used, but for certain analyses of AP subject performance, times for correct responses only are used.

Latencies by block. To check for any possible warm-up, practice, or fatigue effects, a repeated-measures ANOVA was performed on the mean reciprocals of DT's for subjects and blocks, for each note-range condition. In no case was Block a significant variable at $\alpha = .05$, although there was for most conditions a trend suggesting that responses were slightly slower in Block 1, on the average, than in the remaining blocks. It was decided to pool data from the four blocks for all subsequent analyses.

Decision times as a function of note range. In Figure 6, the harmonic mean DT's are plotted against note range in terms of stimulus information.

Insert Figure 6 about here

Generally, the relation is linear, with intercepts ranging from about 250 to 480 msec and slopes ranging from about 66 to 150 for most subjects, and 525 for one deviant NAP subject whose DT's were extremely slow and deliberate. If the data for this deviant subject are ignored, AP subjects are not differentiated from NAP subjects. In fact, the fastest performer, overall, is an NAP subject. Any statistical test of the differences in intercept and slope values between AP and NAP subjects would not seem worthwhile.

At the intercept, the decision time is similar to a simple reaction time; the fact that the mean decision time (over subjects) is somewhat longer than typical values of simple reaction time in other types of experiments may be due to the inclusion of some amount of time to prepare to make an accurate motor response.

The slopes of the curves may be taken to represent the increase in processing time necessary to make an absolute judgment, as a function of the number of alternatives among which judgments are to be made. It can be

demonstrated that the slopes are not an artifact resulting from an increase, with increasing stimulus set size, in average distance of the notes from the starting position in the task. It could be argued that distant notes might exert an influence on DT by causing an increase in the preparation time to move to such notes. Two kinds of evidence can be brought to bear against any claim of such an artifact. First, the correlations of reciprocal DT with the absolute distance of response notes from the starting point are low: in the 64-note range, where there is maximum variance in note distance, these correlations range from -.314 to .170 with a median of .016 for the nine subjects, and these results are similar to those in the 1-note condition, where the correlations range from -.383 to .278 with a median of -.055. Second, mean decision times differ significantly over conditions even for notes in identical regions of the keyboard. This can be demonstrated best with correct response data for the AP subjects (since correct response data for NAP subjects under some conditions are very scanty); the demonstration is restricted to correct response data because otherwise the response notes are not controlled in the same way as the stimulus notes. Table 5 gives, for each of the five AP subjects, mean reciprocal DT's for the same range of stimulus notes, D#4 to F#4, under the 64-, 16-, and 4-note conditions, along with t-tests of the differences between the mean times for the 64- and 16-note conditions combined and those for the 4-note condition. (The combination of the 64- and 16-note data is necessary because there are few instances of these stimulus notes in the 64-note condition, and most of the t-tests between the 64- and 16-note means are nonsignificant.) In every case, the difference is highly significant: it takes longer for a subject to identify these notes when they are alternatives in a large set than when they are alternatives in a small set. Since

similar results can be demonstrated with other note ranges that are in common between conditions, this is true regardless of the position of the stimulus in the set of alternatives. These findings are in accord with Hick's law (Hick, 1952) and other studies of the role of stimulus information in reaction time (e.g., Hyman, 1953). What is somewhat novel in the present data is the large number of alternatives included in the stimulus set. Also, in its method of measuring reaction time without the inclusion of MT, this study does not appear to have precedents in the literature on this subject.

Insert Table 5 about here

Movement times. As might be expected, harmonic means of MT's are a function of note range, but MT's are substantially correlated with distance from the starting point. For the nine subjects, the correlations of reciprocal MT's with absolute note distance in the 64-note condition range from -.517 to -.078 with a median of -.391 ($r_{.05} = .18$); in the 1-note range, they run from -.691 to -.443 with a median of -.617 ($r_{.05} = .25$). In fact, the data provide an excellent confirmation of Fitts' law (Fitts, 1954), whereby MT is a linear function of $\log_2$ (2A/W), where A is the measured distance traveled in a speeded motor response and W is the width of the target. (In the present experiment, the white-note targets on the piano keyboard are about twice the width of the black-note targets.) Since this demonstration is of no immediate interest in the present context, it will not be given here. Also, summary data on MT's will be omitted.

Rate of gain of information for AP subjects. The MT's of the 1-note condition as a function of absolute distance from the starting point can be used to adjust MT's in the other note-range conditions to estimate the amount of those other MT's that is a function of note-range condition and hence is

presumably occupied with some of the decision processing involved in an absolute judgment, or with motor planning and the like. The process of adjustment is illustrated with data from one of the AP subjects (the writer) in Figures 7, 8, and 9. In Figure 7, harmonic mean MT for correct responses is plotted for the 64-, 16-, and 4-note conditions as a function of the average distance of certain groups of stimulus from the starting point in the task. The note-groups are those that are in common between one or more of the stimulus sets; for example, the notes at a distance of -32 to -21 semits from the starting point are among those that are in common to the 64- and 1-note sets; notes at a distance of -2 to +2 semits are common to all four sets. (Data from the 7-note condition are not used in these analyses for various reasons, including the fact that they do not include a full range of semitones, and involved different starting points over blocks.) It is evident that MT is a function

Insert Figures 7, 8, and 9 about here

not only of distance but also of note-range condition. In Figure 8, harmonic mean DT's for this subject are shown as a function of note-range condition and of note distance. While these DT's vary systematically with note-range condition, they do not vary significantly as a function of note distance. In Figure 9, the differences between the values of harmonic mean MT at H_i and H_0 for a given group of stimulus notes are added to the corresponding harmonic mean DT's (H_i = 0, 2, 4, 6) to give values of "DT plus adjusted MT" and the means of the resulting values over note-groups are taken (despite some variation in these values, regarded as nonsignificant).

Similar procedures were followed for data from the remaining AP subjects, and the resulting DT + adjusted MT values are plotted as a function of stimulus

information for each AP subject in Figure 10. The original DT values are also plotted. Since the adjusted MT values were extremely small for AP-1, this subject can be regarded as having done practically all of the decision processing during the DT phase of the task. For the remaining AP subjects, a substantial portion of the MT appeared to have been occupied with some sort of refinement of the decision process.

It would appear that both DT's and adjusted MT's are a linear function of stimulus information. Departures from linearity are probably mainly a function of error variance. Figure 10 shows lines fitted to the values; the reciprocals of the slopes of these lines are shown as values of the rate of gain of information (IG) in bits per second. Those derived from the values of DT's alone (IG_d) are somewhat higher than those derived from values of DT + adjusted MT; the former are based on the assumption that information processing is completed within the DT phase of the task, while the latter assume that some information is processed in the MT phase. In any event, the values of IG for at least the faster of the AP subjects are much higher than some values reported earlier for other stimulus modalities (Bricker, 1955).

Insert Figure 10 about here.

Information transmitted in decision time. We may now make estimates of rates of gain of information for all subjects, but since adjusted movement times are difficult to estimate for NAP subjects because of the paucity of correct responses under some note-range conditions, we use only decision times for all responses in conjunction with the associated estimates of information transmitted. In Figure 11, the harmonic means of decision times for all responses are plotted for all subjects as a function of total information

transmitted under different note-range conditions (again excluding the data from the 7-note condition). In effect, this figure reinterprets the data of

Insert Figure 11 about here

Figure 6 in terms of the data reported in Table 4. The general linearity of the relation between DT and stimulus information is again confirmed, for both AP and NAP subjects. But while the AP and NAP subjects do not generally differ in speed of decision (i.e., in the slopes of the lines relating DT and information transmitted), they differ greatly in the amount of information transmitted per unit of time (i.e., in the rate of gain of information). Rough estimates of these information rate gains are given in Table 6. These estimates are obtained by dividing information transmitted in the 64-note condition by the increase in DT from the 1-note to the 64-note condition. Along with rates of gain for total information, rates are given for octave and chroma information separately. The rates of gain of total information for AP subjects are slightly different from those given previously because they are based on all responses (rather than only correct responses) and on a cruder estimation procedure.

Insert Table 6 about here

Because of the extremely fast (but inaccurate) responses of one of the NAP subjects, and despite the extremely slow responses of another of these subjects, the difference between total IG for AP and NAP subjects is significant only at $\alpha = .10$. As expected, the differences in octave IG are nonsignificant, but it is noteworthy that the differences in chroma IG are significant at $\alpha = .02$. Even for the AP subjects, however, the rates of gain computed separately for chroma and octave information, on the assumption that pitch is a two-

dimensional continuum, are generally not higher than comparable figures for other stimulus modalities as reported by Bricker (1955). This is a further way in which facts about the performance of AP subjects in judging pitches can be made to come in line with parameters estimated in other contexts, but this does not eliminate the possibility that AP subjects represent extremes of ability in the judgment of chroma.

Discussion

Several persistent questions will doubtless have occurred to the reader. Do the persons claiming AP ability studied here truly "have" ability that is somehow different from that of the average person? How good is their ability relative to that of others claiming this ability? Are persons who claim AP ability and who are able to demonstrate it in some reasonable degree merely those present at the upper end of a continuously distributed trait?

In the whole literature of AP ability, no more than around two hundred persons claiming this ability have been reported on, and with few exceptions the reports fail to yield the kind of information from which one could accurately characterize the extent of ability demonstrated or draw any conclusions as to the distribution of ability. Even the definition of AP ability has been under dispute, largely because the methods of measuring it have never been adequately standardized. As Wynn (1973) remarks, "Much of the published work in the field is unfortunately of little value because the authors have not indicated the type of absolute pitch which their subjects possess" (p. 114).

Some of the studies that have been quoted or cited with apparent approval by such reviewers as Ward (1963a, b) and Wynn (1973) turn out, on close examination, to be highly suspect. For example, Oakes (1955) gave an AP test to

88 persons, including 22 persons who claimed AP ability or were regarded by their instructors as having it, but reported and analyzed the data in such a faulty and unsatisfying form that one hesitates to cite them. The test was given by wire-recorder (an instrument of dubious quality) and required subjects to identify 75 different notes struck on a piano tuned to A4 = 443 Hz. He used three methods of scoring the results and displayed cumulative distributions of scores that he claimed were "essentially normal" with no obvious bimodality. Actually, anyone who takes the trouble to convert Oakes' distributions to frequency histograms will recognize that these distributions are highly skewed, positively, and reveal considerable evidence of bimodality and outlying clusters. It is of interest to see how the subjects used in the present study place on these distributions. One of the measures was "absolute error"; apparently no adjustment was made for octave errors. Oakes' best 5 subjects made "average errors" of from 1.55 to 2.45; in the 64-note task of the present study, the AP subjects made average errors (by the same scoring system) ranging from .73 to 1.55 and thus placed for the most part above Oakes' best subjects, while the NAP subjects made average errors ranging from 3.16 to 5.20 and thus placed a little above the median of Oakes' total distribution. Another measure was the number correct out of the 75 notes; converting all values to percentages, we find that the top five percentages in Oakes' distribution were 77, 73, 65, 63, and 62; these may be compared to the percentages for our AP subjects, which were 93, 80, 67, 67, and 48. NAP subjects' percentages, ranging from 15 down to 8, place them slightly better than Oakes' median, which was of course quite low on the scale. One further measure was the number correct, counting octave and 1-semit errors as correct: on this measure our AP subjects placed among or better than Oakes' top 8 performers,

and again our NAP subjects placed a little above the median of all 88 of Oakes' subjects. If Oakes' data are to be regarded as in any way representative of college student populations, our AP subjects appear to be rather exceptional, and our NAP subjects little better than typical unselected persons not claiming AP. It is striking that in each of Oakes' distributions, the region of the scale between where our NAP subjects place and where our AP subjects place has relatively few cases. Although the distributions may be regarded as "continuous," this is largely because the scale itself may be laid out continuously.

A much more reliable and well-reported set of data is that published by Weinert (1929), who, in the course of visits to the principal centers of musical culture in Europe, was able to test 22 musicians claiming AP ability--orchestra conductors, concert performers, and the like. Requiring only chroma judgments of 88 piano notes, he reported data from which it is possible to compute several measures identical to those used in the present study and to compare his subjects with ours (using data from our 64-note task). Among Weinert's 22 AP-claiming subjects, our 5 AP subjects rank about 3, 10, 12, 12, and 17, respectively, in proportion of zero chroma error; they rank about 1.5, 7, 12, 14, and 19 in standard deviation of algebraic chroma error, and 1.5, 9, 11, 14, and 19 in mean absolute chroma error. Most of our AP subjects, therefore, are representative of the better half of Weinert's. Our NAP subjects are clearly below <u>any</u> of Weinert's subjects on all these measures; Weinert tested no NAP subjects.

Considering all these results, we may form a tentative conclusion about the distribution of AP ability in typical cultures of Western civilization. Persons claiming AP ability do indeed form a special class of individuals that can perform AP judgment tasks much better than most individuals, although there

is still considerable variation in their performance, and the mere fact that a person claims AP ability cannot be taken to mean much until this claim is validated by appropriate tests. If it were possible to test a large population for AP judgment ability, the distribution would be very much positively skewed, with a minor mode toward the top end of the scale. Although cases might occur at any point on the scale, there would be very few cases in some region lying between the two modes of the distribution; the point of division between persons "having" AP and those not having it could be established by finding the minimum value of the fitted density function between the two modes. If our hypothesis about the distribution of AP judgment ability is correct, there would be no necessity for setting some arbitrary criterion for the possession of AP ability, such as Bachem's (1937) very stringent requirement that persons be regarded as having "genuine" AP ability only if their average error is less than .1 semit. We would simply conclude that AP ability is a continuously but bimodally distributed trait. This would, however, say nothing about the genesis of the trait; it is a purely descriptive statement.

From the present data, can we say anything about the nature of the ability exhibited among individuals "having" AP ability? One thing seems very clear: the perceptual dispersion variance of AP subjects is very much smaller than that of NAP subjects, particularly when judgments must be made of notes in a stimulus set with many alternatives. In establishing the distribution of AP judgment ability in a large population, as proposed above, the best measure of the trait would be a measure of perceptual dispersion variance, and it may be postulated that such a measure would be most likely to reveal bimodality. It would have to be a measure, however, that would adjust for "octave errors," such as the standard deviation of chroma error developed in the present study.

In statistical theory, bimodality in the distribution of a trait can be interpreted as suggesting that the distribution is a composite of two separate normal distributions, and this lends credence to the idea that has been proposed a number of times in the literature (Bachem, 1950; Révész, 1913) that AP and NAP subjects can use different mechanisms in judging pitches: AP subjects can use tone chromas (i.e., the notes of the musical scale in an octave) as the anchors for their judgments, while NAP subjects can use only tone height, i.e., the pitch of a tone relative to the total pitch frequency spectrum or some part thereof. The use of tone height is analogous to the use of perceived spatial distances in judging the relative position of a point on a line, e.g., judging that a particular point is about one-third of the distance from the left-hand end of the line. We know (Keele, 1973) that people can make fairly accurate judgments of <u>relative</u> position in various sensory dimensions, and there is reason to believe that they can make such judgments in the c e of the pitch dimension. In fact, this type of judgment is the basis of major developments in the theory of the scaling of pitches, i.e., according to a "mel" scale (Stevens & Volkman, 1940). Anyone who has reasonable familiarity with the piano keyboard and what high and low notes sound like can therefore make a reasonably accurate judgment of the relative height of a tone with respect to the piano keyboard, the accuracy sometimes being on the order of an absolute error of 2 or 3 semitones, as Révész (1913, p. 92) observed. Variance in the ability to make such judgments of relative tone height would account for the variance in the primary component of the bimodal distribution of AP judgment ability. Variance in the accuracy with which particular chromas are fixed in long-term memory would account for most of the variance in the secondary component of the distribution.

In the present experiment, however, it was found that accuracy increased for both AP and NAP subjects as size of stimulus set decreased; AP subjects always maintained their lead over NAP subjects, of course. In terms of the notions just presented, this could be interpreted as implying that (1) as stimulus set size decreases, the accuracy of judgment on the basis of tone height is enhanced because a unit of pitch distance, such as the semit, becomes an increasingly larger proportion of the total note range--and thus it is easier to judge relative positions of notes within the range; (2) this fact is the sole basis of the NAP's increased accuracy for smaller set sizes; and (3) AP subjects can use information from tone height just as well as NAP subjects, and this accounts largely for their increased accuracy with smaller set sizes, but in addition they use information from long-term memory traces of tone chromas, and this accounts for their continued superiority over NAP subjects even at the smaller set sizes. However, if the pitch range of the set becomes sufficiently small, such that the perceptual dispersion of a particular tone chroma extends over the range of the stimulus set, the superiority of AP subjects over NAP subjects would disappear. Evidence suggests that this is in fact the case (Siegel, 1974).

One way in which this "two-factor" theory might be tested would be to require judgments based on tone chroma only. If subjects were presented with a note of a particular frequency and asked merely to state whether it is or is not of a designated chroma, regardless of the octave in which it occurs, we would expect AP subjects to be much more successful than NAP subjects, because NAP subjects could not use tone height as a basis for judgment if the notes in this task were chosen from different octaves randomly.

Another major finding of the study was that the speed of judgment increased as set size decreased, for both AP and NAP subjects. This finding is only a general confirmation of Hick's (1952) law, and since the effect was the same for AP and NAP subjects it is probably of little interest or relevance in the interpretation of AP ability. AP subjects were more accurate and transmitted more information per unit of time, but this means only that they had more information available to transmit. The fact that AP subjects were differentiated from NAP subjects primarily in the rate of gain of chroma (as opposed to octave) information, however, constitutes further support of a two-factor theory of AP ability, since octave information is much easier than chroma information to extract from tone height, in the sense that octaves are grosser divisions of the logarithmic frequency spectrum than semitones. Also, acceptance of a two-factor theory of AP makes it easier to reconcile channel capacity estimates for AP subjects with those derived in other contexts, if indeed the concept of channel capacity is at all valid. Laming (1973, p. 173) and Rabbitt (1971) argue that information theory concepts are not appropriate to use in interpreting absolute judgment behavior.

The fact that AP and NAP subjects were not generally different in speed of response is pertinent to the frequently made claim that AP subjects make very rapid pitch identification, while NAP subjects are much more deliberate. But this claim has to do with subjects' behavior in a task where they are not under a set for speed. In the absence of such a set, subject who is uncertain of the correct judgment could be expected to be slow about revealing his uncertainty. In a situation such as that of the present study, where the subject is under pressure to make a rapid response—at least a "guess" or an approximation, the subject who is uncertain of his judgment can indeed

make a rapid response if he is motivated to do so. Actually, one of our NAP subjects apparently chose to make very slow and deliberate responses, despite repeated urgings to make rapid responses.

Throughout this discussion, it has been assumed or suggested that AP subjects are able to use information from "chroma" standards stored in long-term memory. Essentially this is the "internal standard" theory of AP ability that has been discussed by Siegel (1972), but as Siegel herself notes, much more work needs to be done to confirm the theory and to investigate the nature of these internal standards, if they exist. What variance do they have, and how can they be influenced? Is it the case that in all AP subjects, these internal standards correspond one-for-one to the 12 notes of the musical scale, or is it possible that in at least some AP subjects a greater number of standards within an octave have been or can be established? If a two-factor theory of AP ability cannot be confirmed, will this mean, for example, that every note in the musical scale, at least over the compass of commonly used musical instruments, must be regarded as having its own internal standard?

Until a number of questions such as the above have been answered, it is probably not worthwhile to concern oneself with whether AP ability is inherited or acquired, whether it can be improved, or whether it can be lost. The fact that some individuals can make unusually accurate pitch judgments will still be remarkable, even if it becomes possible to explain how they can do so.

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Table 1

Repeated Measures ANOVA Results for Arcsin-Transformed Proportions Strictly Correct, for Different Subblocks (Note-Ranges)

Tabled values are back-transformed means (proportions correct) by block, N = 9

Note Range	Block 1	Block 2	Block 3	Block 4	Block All	Block $F_{3,24}$	Subject $F_{8,27}$
64	.291	.436	.358	.412	.373	3.14*	33.70**
16	.538	.685	.649	.634	.628	2.98	39.37**
7	.733	.716	.878	.846	.798	3.73*	12.51**
4	.755	.908	.934	.845	.868	2.99	4.84**
1	.972	.969	.976	.946	.967	1.29	2.27

*p < .05; **p < .01

Table 2

Analysis of Errors, 64-Note-Range Condition

Statistic	EAP Subjects 1	2	3	4	TAP Subject 5	All AP Subjects Mean	NAP Subjects 6	7	8	9	All NAP Subjects Mean	$t_{(7)}$
Number of responses	125	121	128	127	127		127	122	127	113		
Total errors												
Proportion zero errors	0.824	0.769	0.617	0.457	0.606	0.655	0.150	0.049	0.087	0.097	0.096	7.36**
Mean algebraic error (semits)	0.568	0.124	-0.156	0.968	1.055	0.512	0.205	2.492	1.345	3.614	1.914	- 2.01
S. D. algebraic error (semits)	4.009	2.455	3 501	3.051	3.618	3.327	4.256	6.057	5.245	6.749	5.577	- 4.02**
Mean absolute error (semits)	1.416	0.736	1.391	1.551	1.606	1.340	3.165	5.033	4.669	5.203	4.518	- 7.14**
S. D. absolute error (semits)	3.793	2.345	3.217	2.800	3.410	3.113	2.853	4.192	4.333	4.504	3.970	- 1.96
Chroma errors												
Proportion zero errors	0.928	0.802	0.672	0.480	0.669	0.710	0.158	0.107	0.094	0.142	0.125	6.82**
Proportion zero errors (corrected)	0.922	0.784	0.642	0.433	0.639	0.684	0.079	0.024	0.012	0.063	0.044	6.83**
White-note bias	0.915	0.731	0.899	0.716	0.521	0.756	0.594	0.918	0.654	0.877	0.861	- 1.01
Mean algebraic error (semits)	-0.008	0.025	-0.062	0.307*	0.016	0.055	-0.173	0.229	0.780**	0.283	0.280	- 1.20
S. D. algebraic error (semits)	0.268	0.698	0.916	1.667	1.079	0.926	2.881	3.067	3.267	3.343	3.140	- 8.01**
Mean absolute error (semits)	0.720	0.273	0.438	0.953	0.535	0.454	2.346	2.574	2.842	2.761	2.631	-11.27**
S. D. absolute error (semits)	0.258	0.643	0.808	1.402	0.937	0.810	1.681	1.684	1.790	1.906	1 765	- 4.40**
Octave errors												
Proportion zero errors	0.888	0.959	0.914	0.945	0.898	0.921	0.874	0.697	0.772	0.672	0.754	3.91**
Mean algebraic error (octaves)	0.048	0.008	-0.008	0.055	0.087	0.038	0.032	0.188	0.088	0.236	0.136	- 2.71*
S. D. algebraic error (octaves)	0.331	0.203	0.293	0.228	0.308	0.273	0.354	0.517	0.443	0.588	0.476	- 3.89**
Mean absolute error (octaves)	0.112	0.041	0.086	0.055	0.102	0.079	0.126	0.303	0.236	0.336	0.250	- 3.93**
S. D. absolute error (octaves)	0.315	0.199	0.280	0.228	0.303	0.265	0.332	0.460	0.443	0.491	0.431	- 4.20**

*p < .05; **p < .01; otherwise nonsignificant at α = .05.

Table 3

Analysis of Errors, 16-, 7-, 4-, and 1-Note Ranges

Statistic	EAP Subjects 1	2	3	4	TAP Subject 5	All AP Subjects Mean	NAP Subjects 6	7	8	9	All NAP Subjects Mean	$t_{(7)}$
16-Note Range												
Number of responses	64	62	63	64	63		63	64	64	60		t
Proportion of zero chroma errors	0.953	0.919	0.857	0.797	0.857	0.877	0.286	0.266	0.281	0.167	0.250	15.88**
Proportion zero chroma errors (cor.)	0.949	0.912	0.845	0.779	0.845	0.866	0.217	0.197	0.214	0.091	0.194	14.15**
White-note bias	1.019	0.824	0.305	0.796	0.410	0.671	0.992	0.801	0.825	0.613	0.808	- 0.82
Mean algebraic chroma errors (semits)	-0.016	0.081*	0.016	0.000	0.159*	0.048	-0.238	0.203	0.359	-0.550	-0.056	0.56
S. D. algebraic chroma errors (semits)	0.216	0.272	0.378	0.586	0.510	0.392	1.883	2.399	2.102	2.341	2.181	-13.69**
Mean absolute chroma errors (semits)	0.047	0.081	0.143	0.250	0.190	0.142	1.381	1.828	1.547	1.850	1.652	-13.97**
S. D. absolute chroma errors (semits)	0.211	0.272	0.350	0.530	0.499	0.373	1.302	1.567	1.468	1.726	1.516	-10.87**
7-Note Range												
Number of responses	55	56	56	56	56		54	56	56	54		
Proportion of zero chroma errors	0.964	0.929	0.893	0.946	1.000	0.946	0.531	0.500	0.518	0.411	0.490	14.60**
Mean algebraic chroma errors (semits)	0.018	0.107*	0.000	-0.107	0.000	0.004	-0.185	-0.196	-0.036	-0.426	-0.211	2.66*
S. D. algebraic chroma errors (semits)	0.301	0.409	0.463	0.450	0.000	0.325	1.765	1.747	2.220	2.174	1.976	-11.11**
Mean absolute chroma errors (semits)	0.054	0.107	0.143	0.107	0.000	0.082	1.111	1.125	1.571	1.389	1.299	-11.99**
S. D. absolute chroma errors (semits)	0.294	0.409	0.440	0.450	0.000	0.318	1.383	1.350	1.568	1.726	1.507	- 9.69**
4-Note Range												
Number of responses	31	31	32	32	32		32	31	32	32		
Proportion of zero chroma errors	0.936	1.000	1.000	1.000	0.875	0.962	0.531	0.742	0.688	0.656	0.654	6.35**
Proportion zero chroma errors (cor.)	0.913	1.000	1.000	1.000	0.833	0.949	0.375	0.659	0.583	0.542	0.541	6.34**
White-note bias	0.907	(.778)+	(.602)+	(.756)+	0.691	0.747	0.500	0.708	0.575	0.705	0.622	1.70
Mean algebraic chroma errors (semits)	0.000	0.000	0.000	0.000	0.125	0.025	0.000	0.129	0.094	-0.125	0.024	0.01
S. D. algebraic chroma errors (semits)	0.254	0.000	0.000	0.000	0.331	0.117	1.000	0.491	0.879	0.650	0.755	- 4.92**
Mean absolute chroma errors (semits)	0.065	0.000	0.000	0.000	0.125	0.038	0.625	0.258	0.406	0.375	0.416	- 5.18**
S. D. absolute chroma errors (semits)	0.246	0.000	0.000	0.000	0.331	0.115	0.781	0.438	0.785	0.545	0.637	- 4.67**
1-Note Range												
Number of responses	59	63	47	63	63		64	63	61	63		
Proportion of zero chroma errors	0.932	0.936	1.000	0.952	1.000	0.964	0.969	0.952	0.934	0.984	0.960	0.22
Mean algebraic chroma errors (semits)	-0.102	0.079	0.000	0.032	0.000	0.002	0.047	0.079	0.098	0.079	0.076	- 2.12
S. D. algebraic chroma errors (semits)	0.399	0.324	0.000	0.307	0.000	0.206	0.276	0.370	0.393	0.625	0.416	- 1.80
Mean absolute chroma errors (semits)	0.102	0.079	0.000	0.064	0.000	0.049	0.047	0.079	0.098	0.079	0.076	- 1.06
S. D. absolute chroma errors (semits)	0.399	0.324	0.000	0.302	0.000	0.205	0.276	0.370	0.393	0.370	0.352	- 1.48

+Since the values are indeterminate, the means of the values for the 64- and 16-note ranges have been substituted for the computation of t and W.
*p < .05; **p < .01; otherwise nonsignificant at α = .05.

Table 4

Mean Information Transmitted

	Chance	Max.	AP Subjects (N = 5) $\bar{x}$	$\hat{s}$	NAP Subjects (N = 4) $\bar{x}$	$\hat{s}$	$t_{(7)}$
<u>64-Note Range</u>							
Chroma (I_c)	.583	3.585	3.031	.350	1.268	.116	9.54**
Prop. possible			.816	.117	.228	.034	
Octave (I_o)	1.056	2.415	2.289	.048	2.022	.145	3.92**
Prop. possible			.908	.036	.710	.107	
Total (I_t)	1.639	6.000	5.321	.334	3.290	.233	10.25**
Prop. possible			.844	.077	.378	.053	
<u>16-Note Range</u>							
Chroma (I_c)	1.116	3.585	3.376	.111	1.872	.167	16.25**
Prop. possible			.920	.043	.344	.064	
Octave (I_o)	- .142	.415	.415	.000	.389	.037	1.58
Prop. possible			1.000	.000	.937	.090	
Total (I_t)	.973	4.000	3.791	.111	2.261	.194	14.95**
Prop. possible			.931	.034	.426	.065	
<u>7-Note Range</u>							
Chroma (I_c)	1.137	3.585	3.479	.074	2.308	.170	14.02**
Prop. possible			.959	.030	.478	.070	
Octave (I_o)	-1.166	- .778	- .778	.000	- .800	.044	1.14
Prop. possible			1.000	.000	.943	.114	
Total (I_t)	- .029	2.807	2.701	.074	1.508	.175	13.96**
Prop. possible			.963	.026	.542	.062	
<u>4-Note Range</u>							
Chroma (I_c)	2.059	3.585	3.525	.089	2.992	.185	5.73**
Prop. possible			.961	.058	.611	.121	

**$p < .01$.

Table 5

Comparison of Mean Reciprocals of Decision Times for Correct Responses to the Same Notes Under Different Note-Range Conditions
N = 5 AP Subjects

Subject	Condition	Reciprocals of DT's for Correct Responses					
		n	$\bar{X}$	S.D.	t	df	p
EAP-1	64-note	6	1.354	.282	-2.60	19	< .02
	16-note	15	1.642	.170			
	(combined)	21	1.551	.251	-2.72	46	< .01
	4-note	29	1.854	.430			
EAP-2	64-note	6	1.416	.250	-1.70	19	n. s.
	16-note	15	1.701	.356			
	(combined)	21	1.620	.354	-4.67	50	< .01
	4-note	31	2.041	.282			
EAP-3	64-note	5	.875	.282	-0.06	16	n. s.
	16-note	13	.883	.238			
	(combined)	18	.880	.251	-4.14	48	< .01
	4-note	32	1.247	.316			
EAP-4	64-note	3	1.194	.258	-1.14	14	n. s.
	16-note	13	1.388	.244			
	(combined)	16	1.352	.258	-6.89	46	< .01
	4-note	32	1.993	.315			
TAP-5	64-note	4	.852	.395	0.07	16	n. s.
	16-note	14	.841	.195			
	(combined)	18	.843	.254	-3.19	44	< .01
	4-note	28	1.166	.367			

Table 6

Computation of Rates of Gain of Information (IG_d) Based on Decision Times

Subject	Harmonic Means of Decision Times (All Responses) 64-note	1-note	Δ	Information Transmitted in 64-Note Condition I_t	I_o	I_c	Estimated Values of (IG_d) (= I/Δ) Total	Octave	Chroma
EAP-1	.741	.320	.421	5.708	2.237	3.471	13.56	5.32	8.25
EAP-2	.775	.308	.467	5.573	2.350	3.223	11.93	5.03	6.90
EAP-3	1.147	.261	.886	5.280	2.280	3.001	5.96	2.57	3.39
EAP-4	.955	.400	.555	4.858	2.328	2.531	8.75	4.20	4.56
TAP-5	1.405	.477	.928	5.185	2.254	2.932	5.59	2.43	3.16
Mean for AP Subjects	1.005	.353	.651	5.321	2.289	3.031	9.16	3.91	5.25
$\hat{\sigma}$	.276	.085	.239	.334	.048	.350	3.54	1.35	2.24
NAP-6	1.098	.309	.789	3.638	2.215	1.423	4.61	2.81	1.80
NAP-7	1.228	.420	.808	3.196	1.934	1.261	3.96	2.39	1.56
NAP-8	.654	.250	.404	3.189	2.047	1.142	7.89	5.07	2.83
NAP-9	3.472	.318	3.154	3.290	1.890	1.248	1.04	0.60	0.40
Mean for NAP Subjects	1.613	.324	1.289	3.290	2.022	1.268	4.38	2.72	1.65
$\hat{\sigma}$	1.264	.071	1.257	.233	.145	.116	2.81	1.84	1.00
$t_{(7)}$	-1.06	0.54	-1.13	10.25	3.92	9.54	2.19	1.13	2.96
p	n. s.	n. s.	n. s.	< .01	< .01	< .01	< .10	n. s.	< .02

Figure Captions

Figure 1. Proportions of strictly correct responses, by block, for data pooled separately for AP and NAP subjects, under five note-range conditions.

Figure 2. Response error distributions, for data pooled separately for AP and NAP subjects, under five note-range conditions. (a) 64-note range; (b) 16-note range; (c) 7-note, 4-note, and 1-note ranges.

Figure 3. Proportions of correct responses for individual subjects under the 4-note (2 bit), 16-note (4 bit), and 64-note (6 bit) note-range conditions, corrected for white-note bias and chance success.

Figure 4. Mean information transmitted (in bits) as a function of stimulus information (bits), for individual subjects. In the upper part of the figure are points for total information transmitted; in the lower right are points for octave information.

Figure 5. Mean chroma information transmitted (in bits) as a function of stimulus information (bits), for individual subjects.

Figure 6. Harmonic means of decision times for all responses, in msec., as a function of stimulus information (bits), for individual subjects.

Figure 7. Harmonic means of movement times (MT's), in msec., for correct responses, AP subject 2, as a function of semits from starting point, for four note-range conditions.

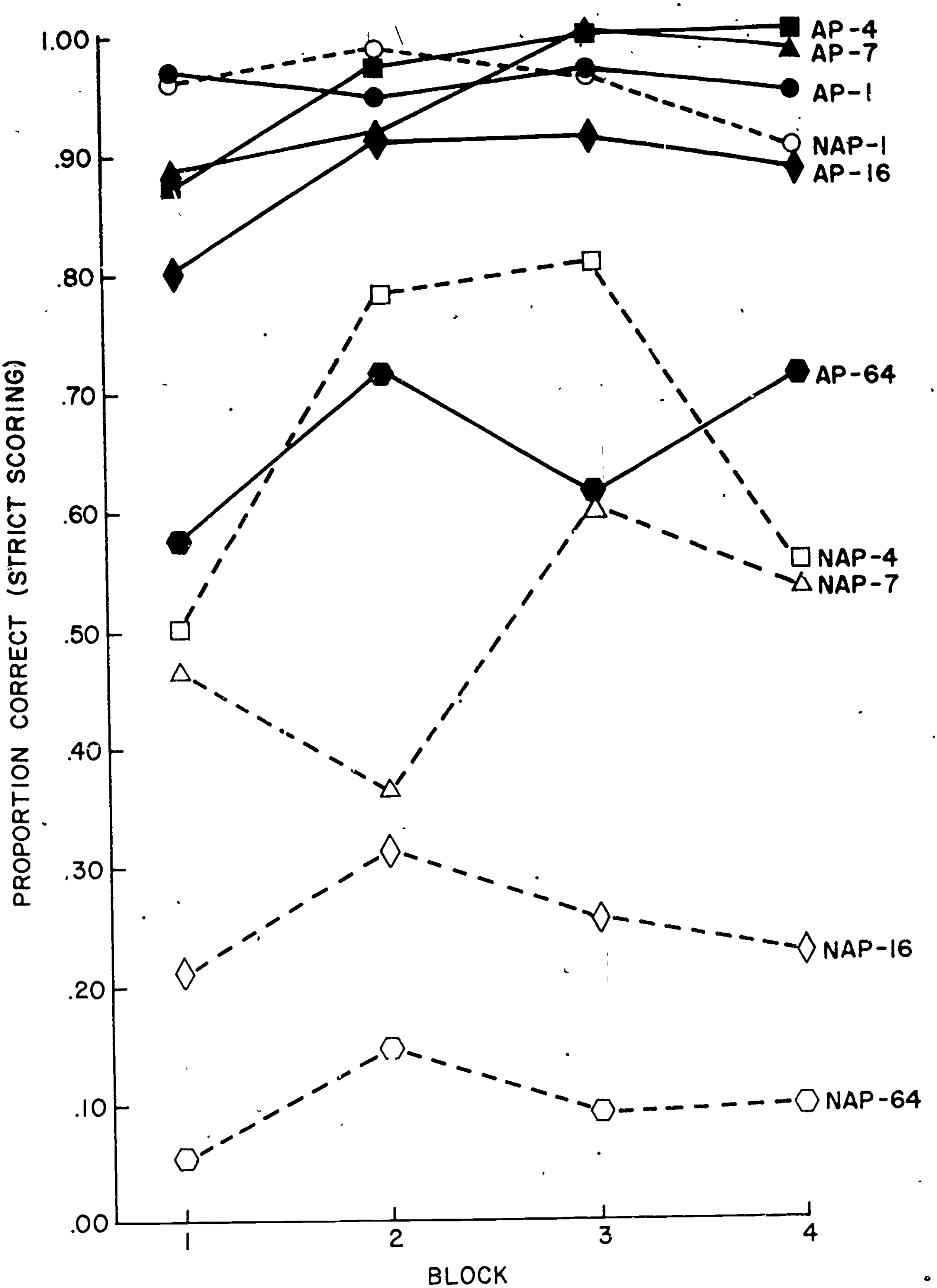
Figure 8. Harmonic means of decision times (DT's), in msec., for correct responses, AP subject 2, as a function of semits from starting point, for four note-range conditions.

Figure 9. Values of decision plus adjusted movement times, in msec., for correct responses, AP subject 2, as a function of semits from starting

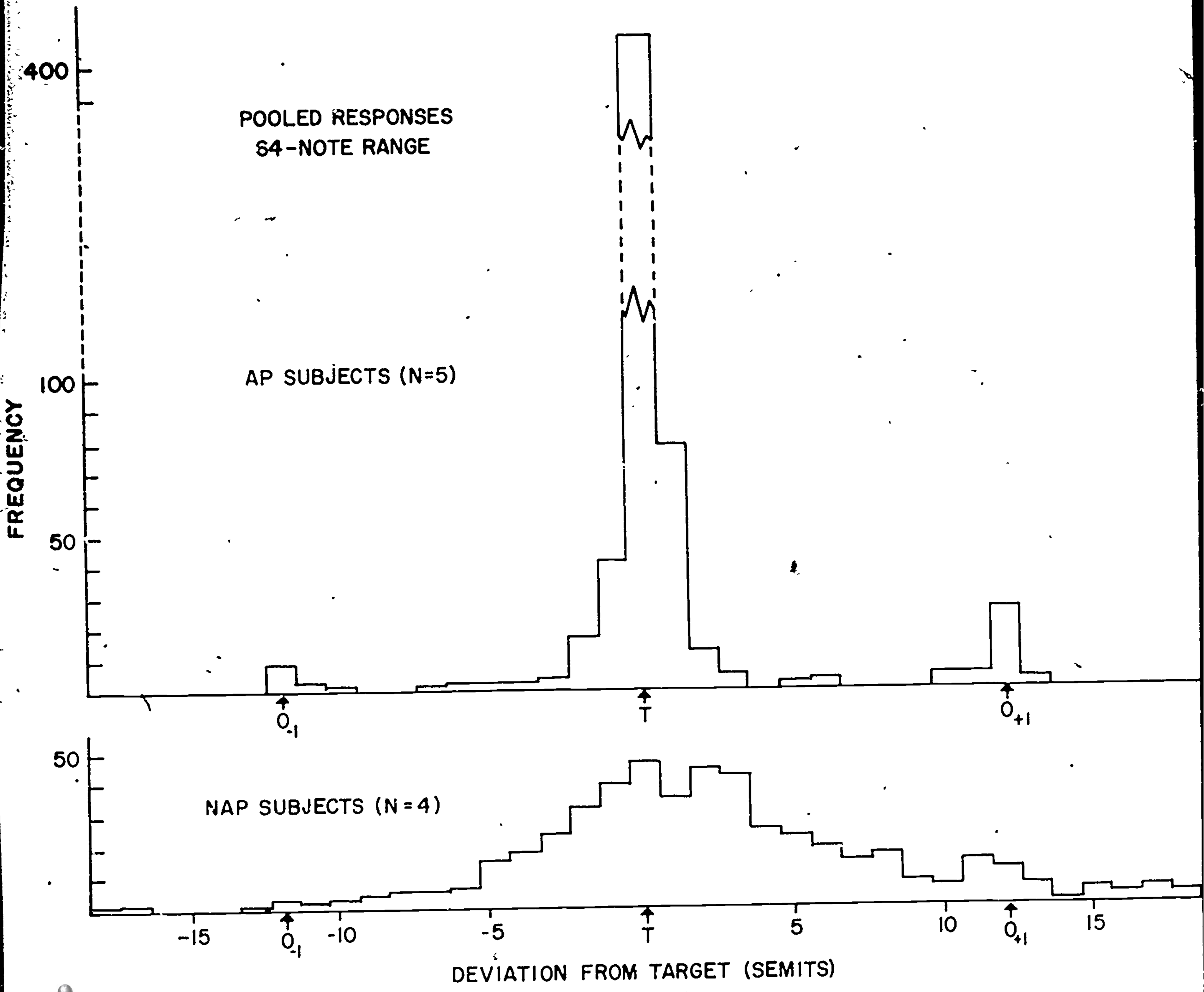
point, for four note-range conditions. Horizontal lines indicate means of values over note groups.

Figure 10. Graphs for individual AP subjects showing response times as a function of stimulus information (bits). Solid lines and filled circles are for decision plus adjusted movement times; broken lines and open circles are for decision times alone. All values are based on estimates from correct responses only. The computation of values of IG is explained in the text.

Figure 11. Harmonic means of decision times, in msec., as related to total information transmitted under four note-range conditions, for individual subjects.

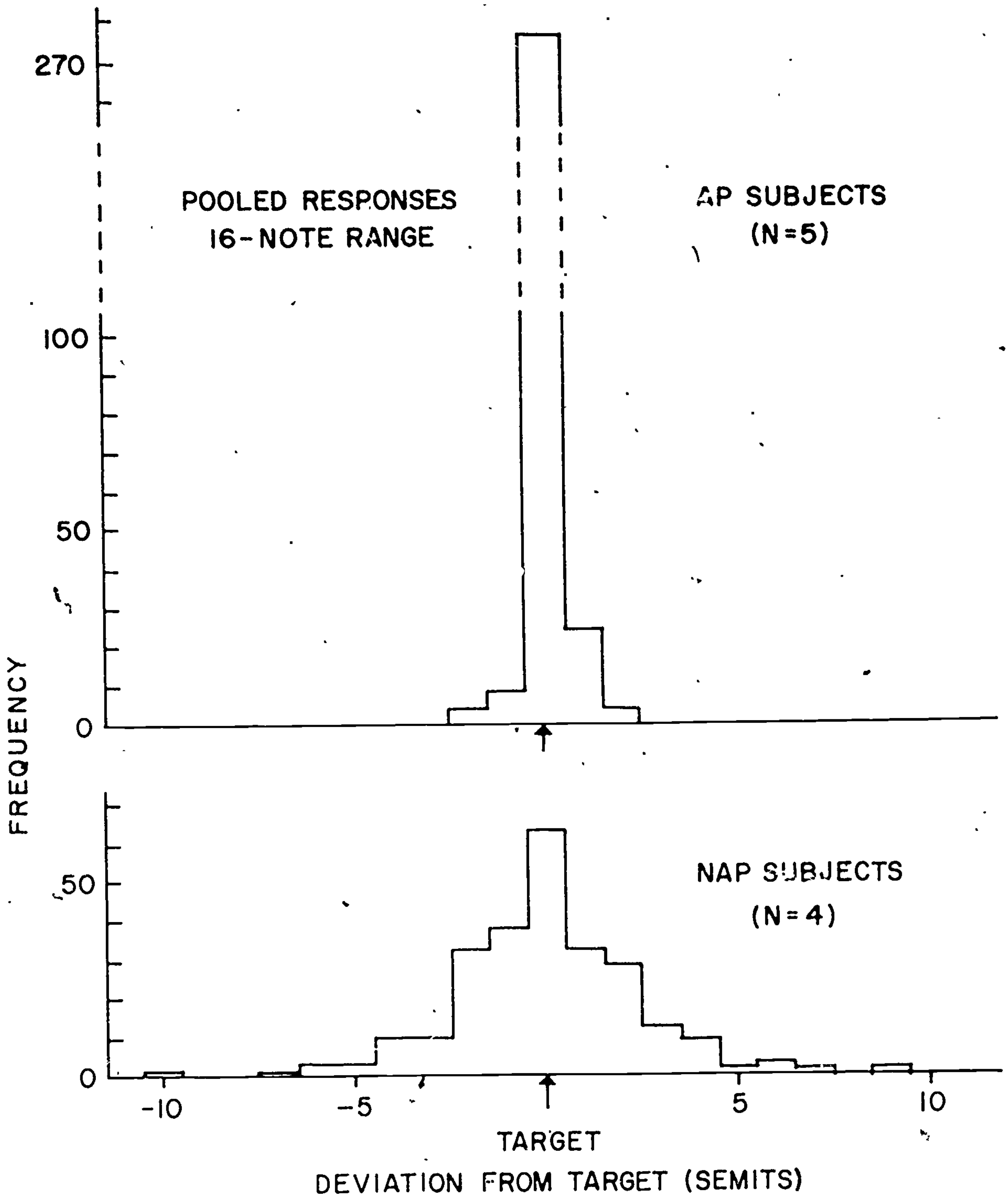

1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
PROPORTION CORRECT (STRICT SCORING)
AP-4
AP-7
AP-1
NAP-1
AP-16
AP-64
NAP-4
NAP-7
NAP-16
NAP-64
1
2
3
4
BLOCK

FIGURE



POOLED RESPONSES
64-NOTE RANGE
AP SUBJECTS (N=5)
NAP SUBJECTS (N=4)
FREQUENCY
400
100
50
50
O_{-1}
T
O_{+1}
-15
-10
-5
5
10
15
DEVIATION FROM TARGET (SEMITS)

FIGURE 2a.


POOLED RESPONSES
16-NOTE RANGE
AP SUBJECTS
(N=5)
NAP SUBJECTS
(N=4)
FREQUENCY
270
100
50
0
50
0
-10
-5
5
10
TARGET
DEVIATION FROM TARGET (SEMITS)

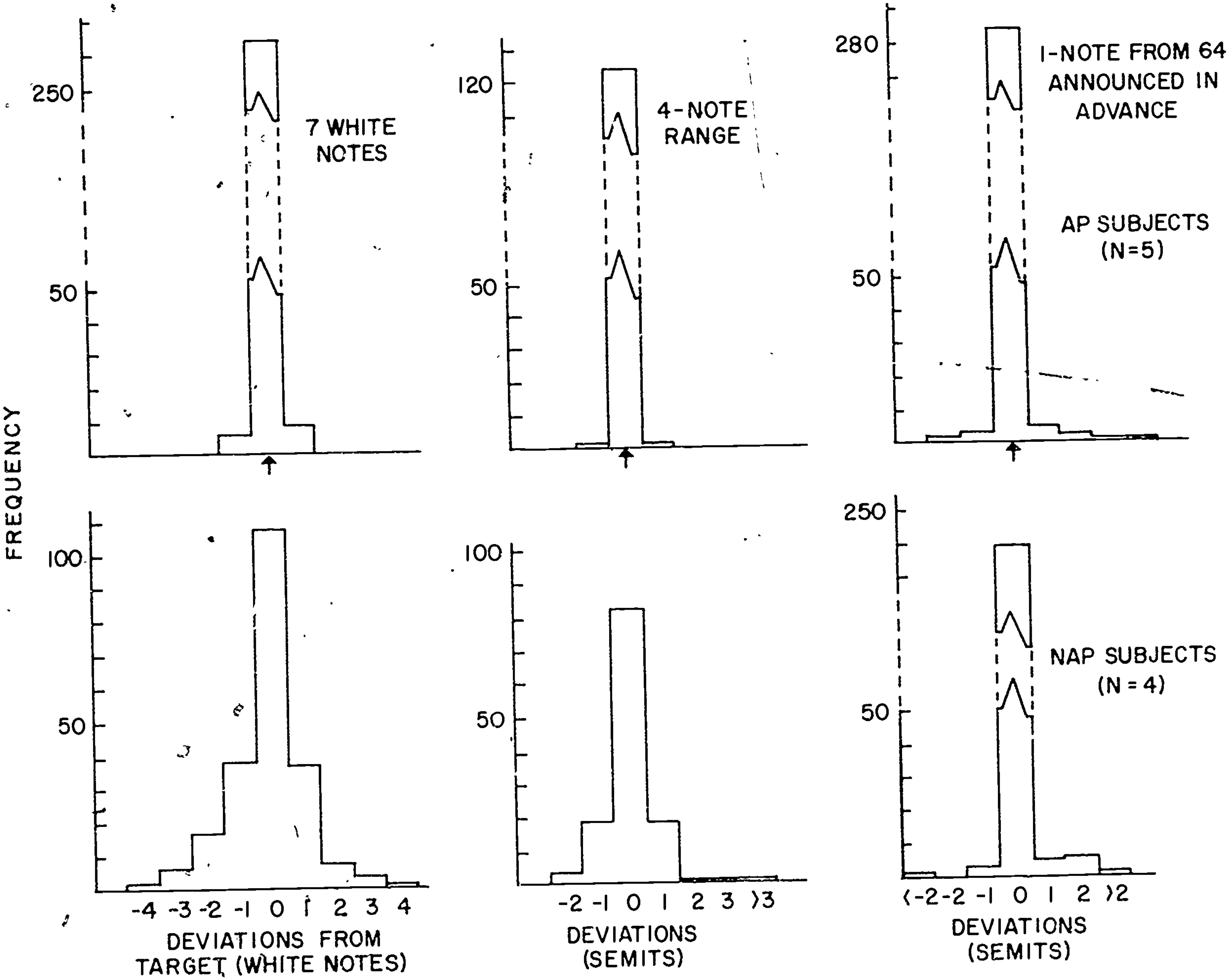

FREQUENCY
250
50
100
7 WHITE NOTES
-4 -3 -2 -1 0 1 2 3 4
DEVIATIONS FROM TARGET (WHITE NOTES)
120
50
100
4-NOTE RANGE
-2 -1 0 1 2 3 >3
DEVIATIONS (SEMITS)
280
50
250
1-NOTE FROM 64 ANNOUNCED IN ADVANCE
AP SUBJECTS (N=5)
NAP SUBJECTS (N = 4)
<-2 -2 -1 0 1 2 >2
DEVIATIONS (SEMITS)

FIGURE 2c.

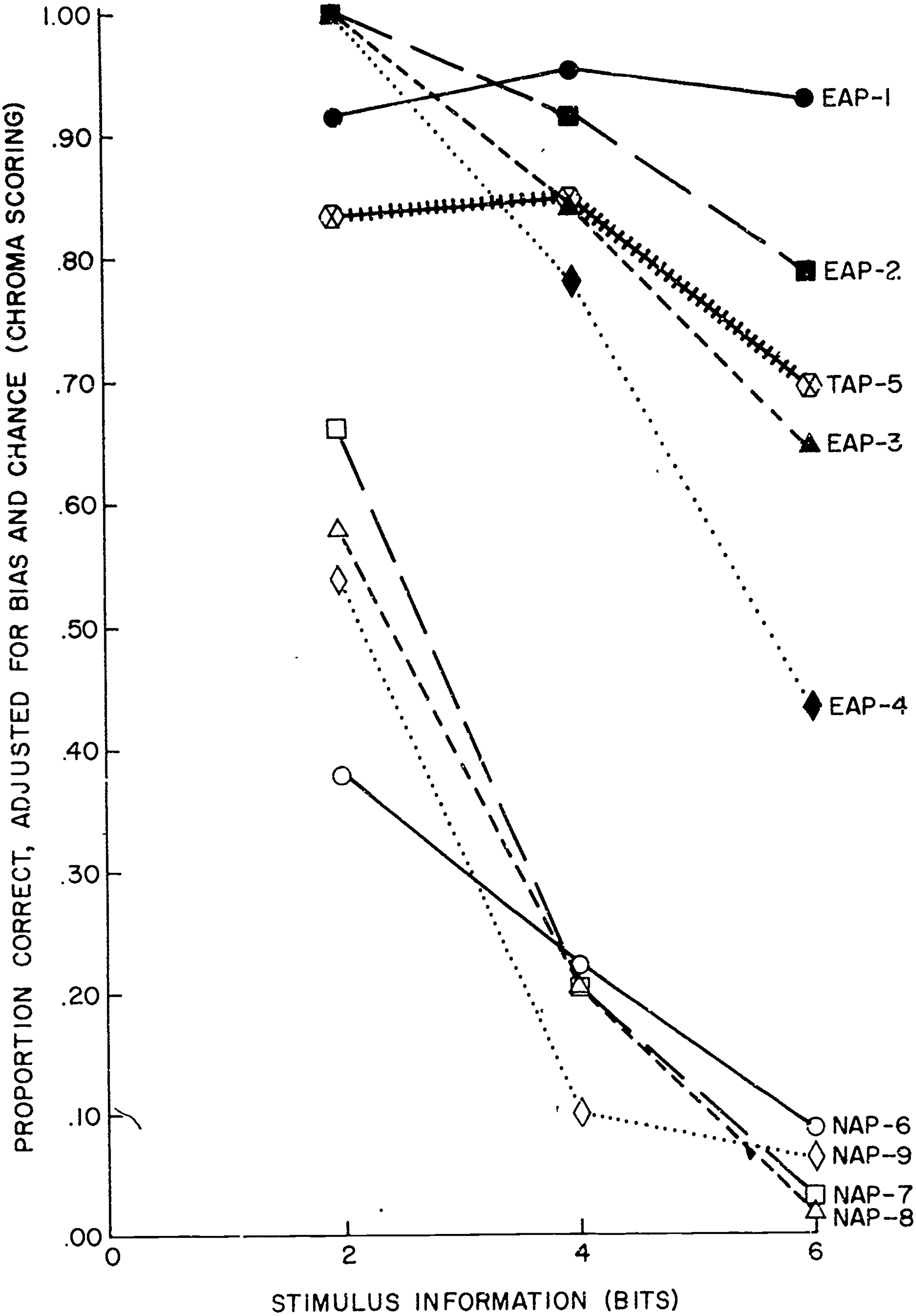
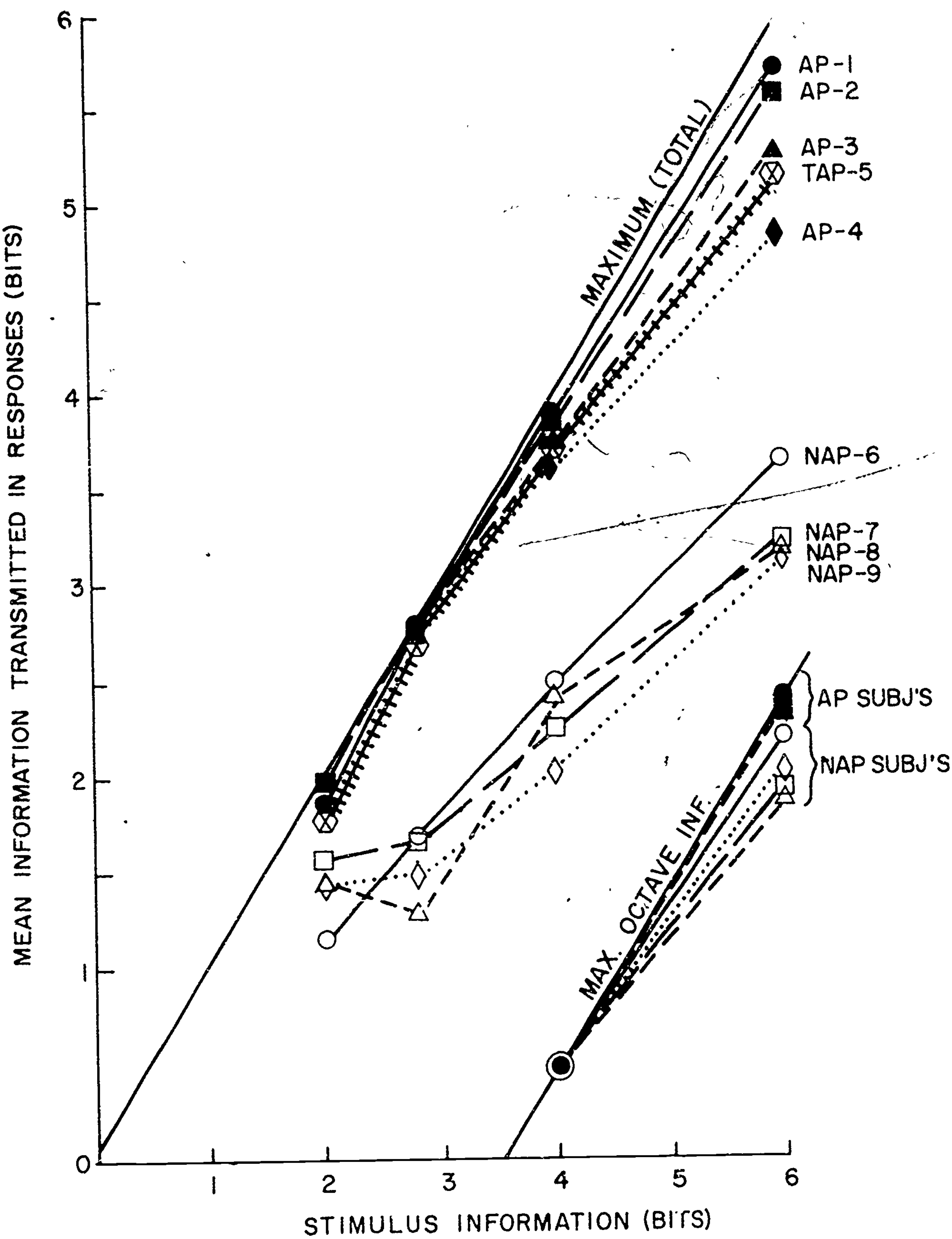

1.00
.90
.80
.70
.60
.50
.40
.30
.20
.10
.00
PROPORTION CORRECT, ADJUSTED FOR BIAS AND CHANCE (CHROMA SCORING)
0
2
4
6
STIMULUS INFORMATION (BITS)
EAP-1
EAP-2
TAP-5
EAP-3
EAP-4
NAP-6
NAP-9
NAP-7
NAP-8

FIGURE 3.



MEAN INFORMATION TRANSMITTED IN RESPONSES (BITS)
STIMULUS INFORMATION (BITS)
MAXIMUM (TOTAL)
MAX. OCTAVE INF.
AP-1
AP-2
AP-3
TAP-5
AP-4
NAP-6
NAP-7
NAP-8
NAP-9
AP SUBJ'S
NAP SUBJ'S

FIGURE 4.

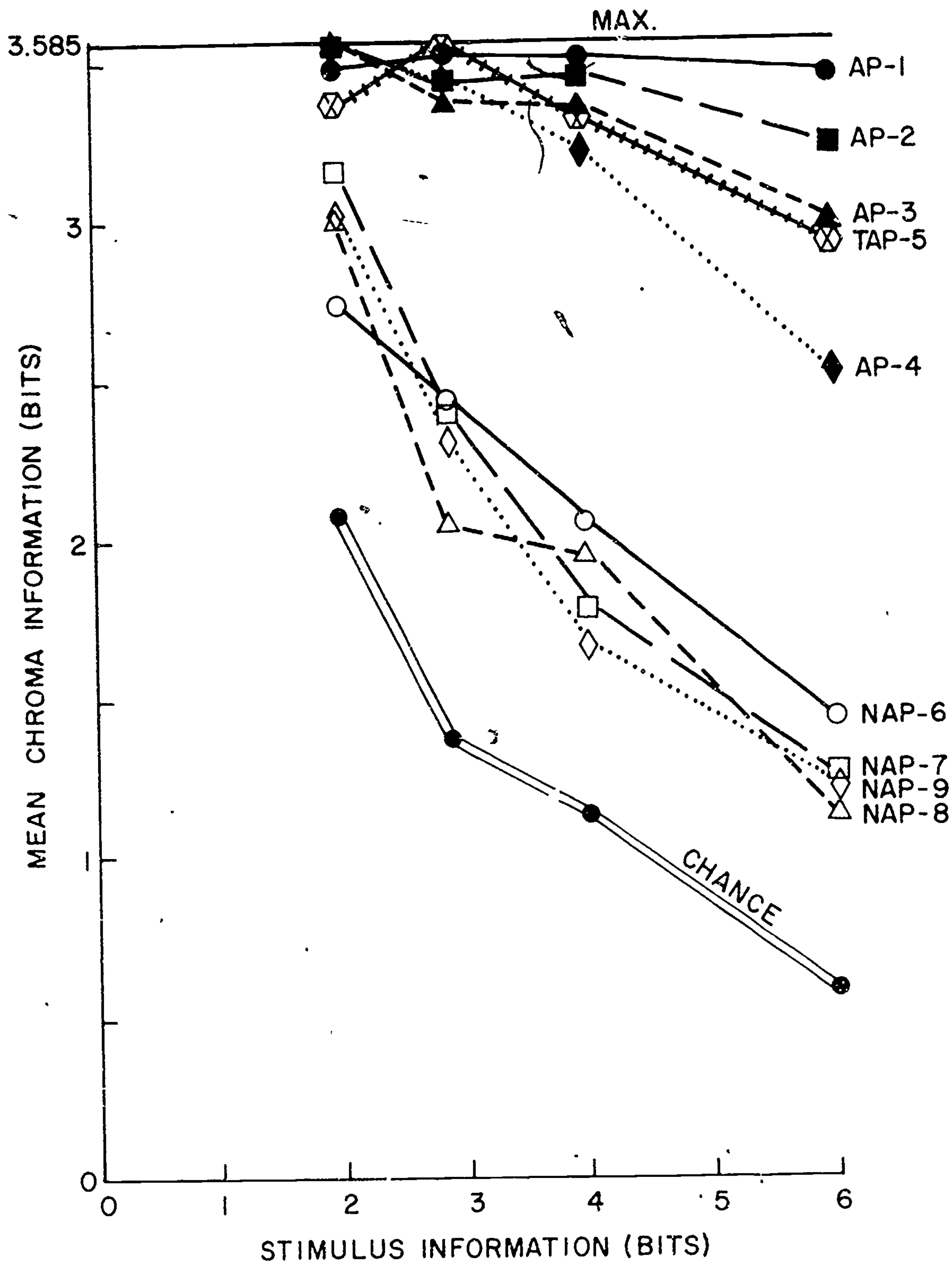

MAX.
3.585
3
2
1
0
AP-1
AP-2
AP-3
TAP-5
AP-4
NAP-6
NAP-7
NAP-9
NAP-8
CHANCE
MEAN CHROMA INFORMATION (BITS)
0
1
2
3
4
5
6
STIMULUS INFORMATION (BITS)

FIGURE 5.

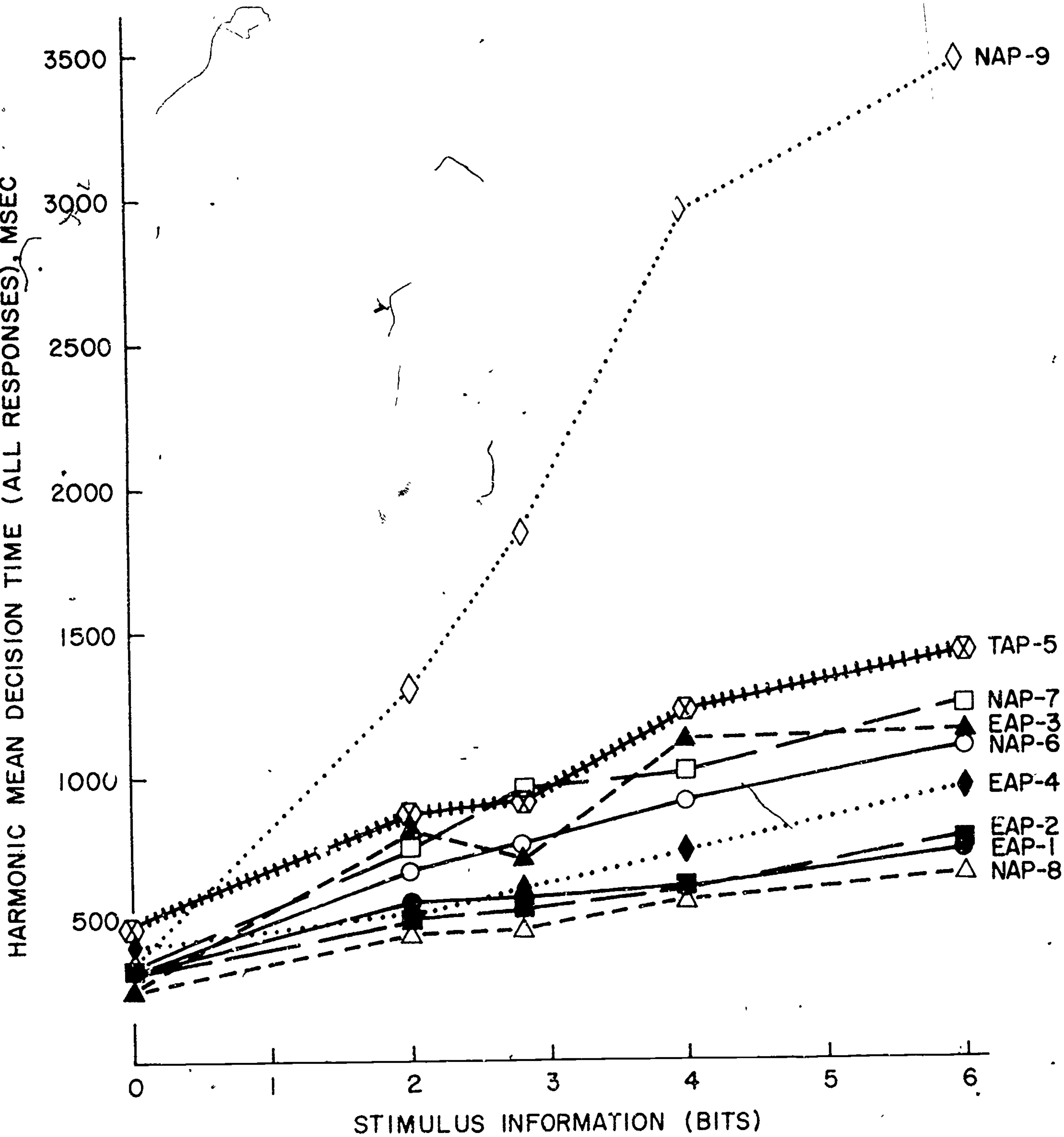

HARMONIC MEAN DECISION TIME (ALL RESPONSES), MSEC
3500
3000
2500
2000
1500
1000
500
0
1
2
3
4
5
6
STIMULUS INFORMATION (BITS)
NAP-9
TAP-5
NAP-7
EAP-3
NAP-6
EAP-4
EAP-2
EAP-1
NAP-8

FIGURE 6.

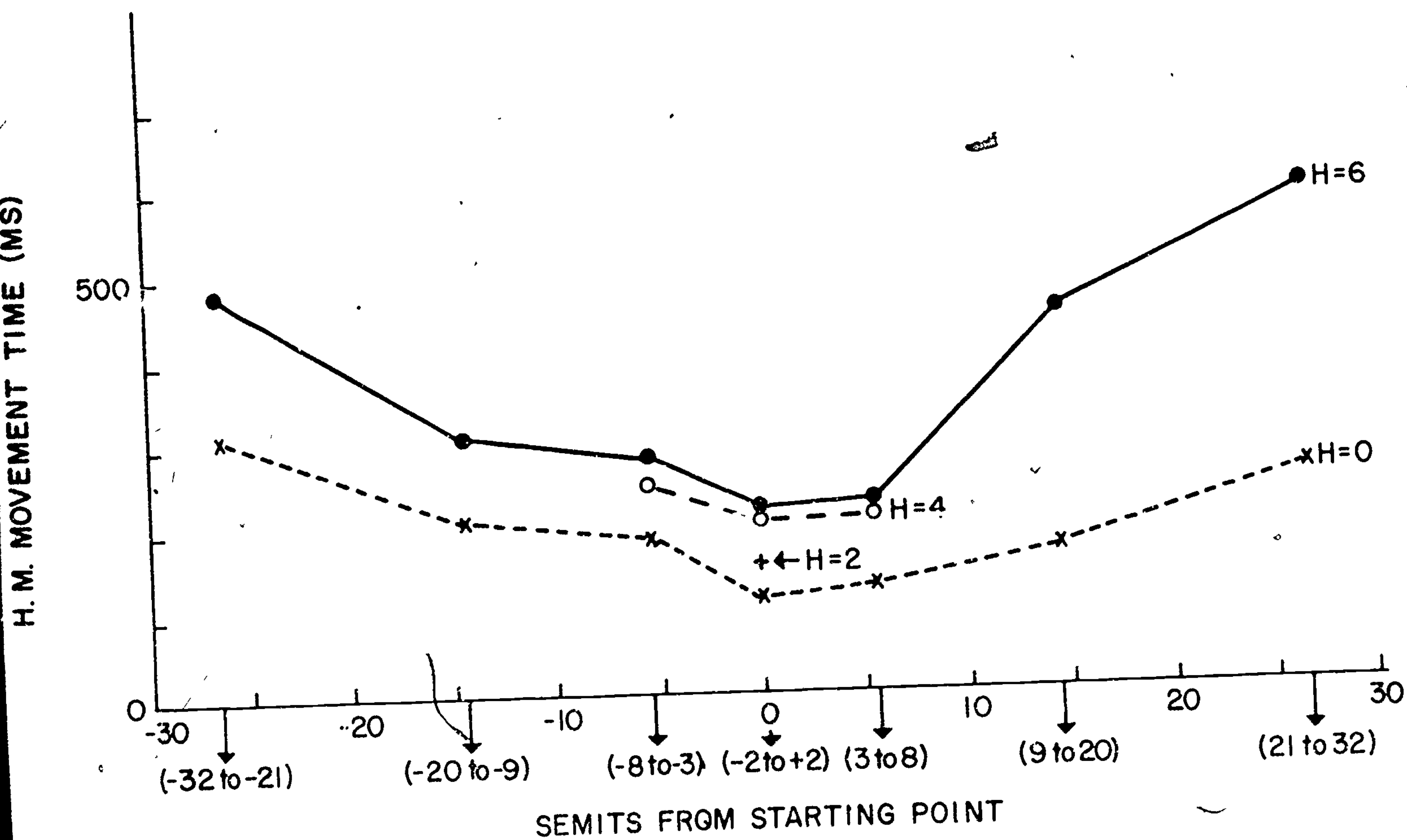

H. M. MOVEMENT TIME (MS)
500
0
H=6
H=4
H=2
H=0
-30
-20
-10
0
10
20
30
(-32 to -21)
(-20 to -9)
(-8 to -3)
(-2 to +2)
(3 to 8)
(9 to 20)
(21 to 32)
SEMITS FROM STARTING POINT

FIGURE 7.

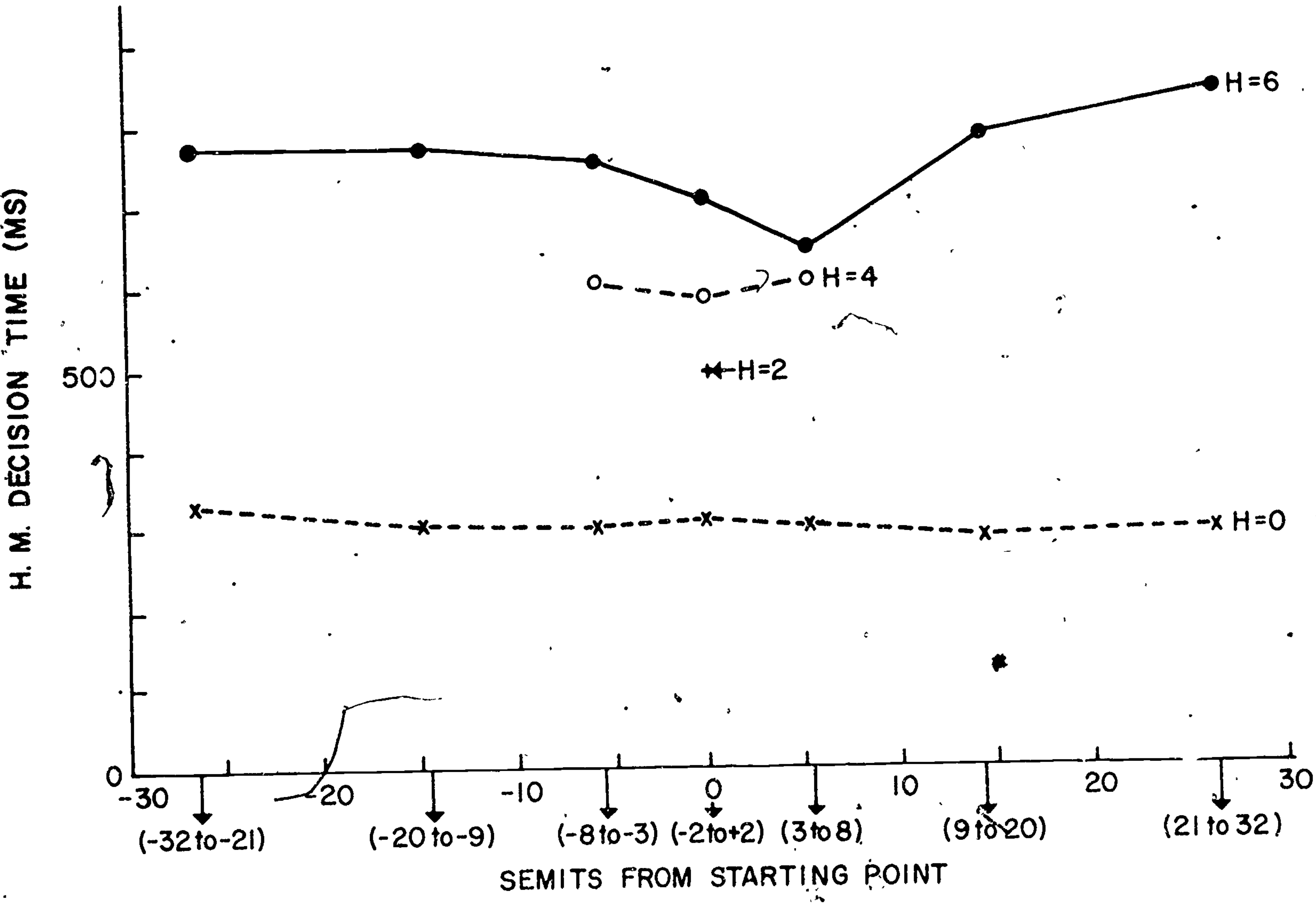

H. M. DECISION TIME (MS)
500
0
H=6
H=4
H=2
H=0
-30
-20
-10
0
10
20
30
(-32 to -21)
(-20 to -9)
(-8 to -3)
(-2 to +2)
(3 to 8)
(9 to 20)
(21 to 32)
SEMITS FROM STARTING POINT

FIGURE 8.

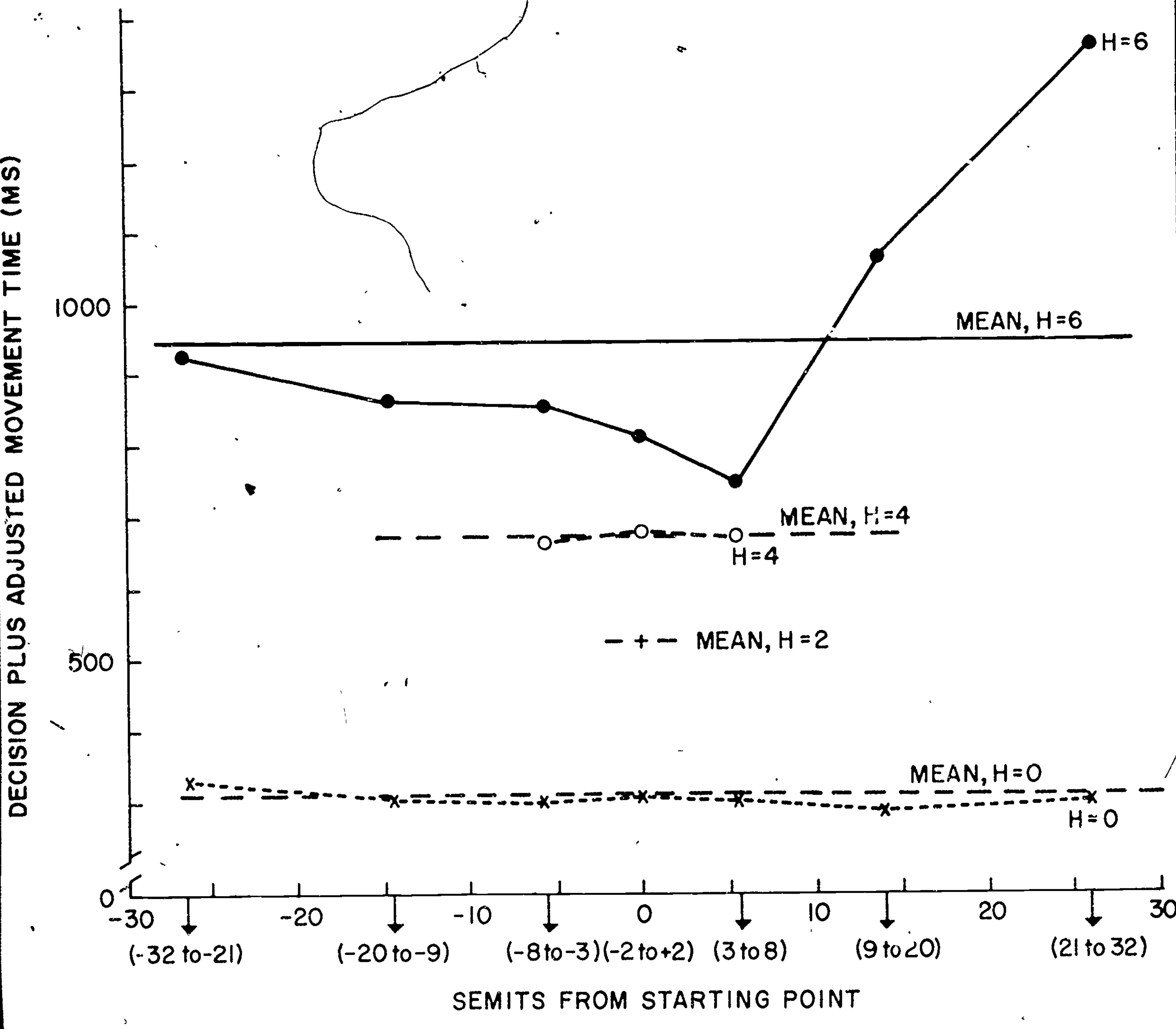

H=6
MEAN, H=6
MEAN, H=4
H=4
— + — MEAN, H=2
MEAN, H=0
H=0
DECISION PLUS ADJUSTED MOVEMENT TIME (MS)
1000
500
0
-30
-20
-10
0
10
20
30
(-32 to-21)
(-20 to-9)
(-8 to-3)
(-2 to+2)
(3 to 8)
(9 to 20)
(21 to 32)
SEMITS FROM STARTING POINT

FIGURE 9.

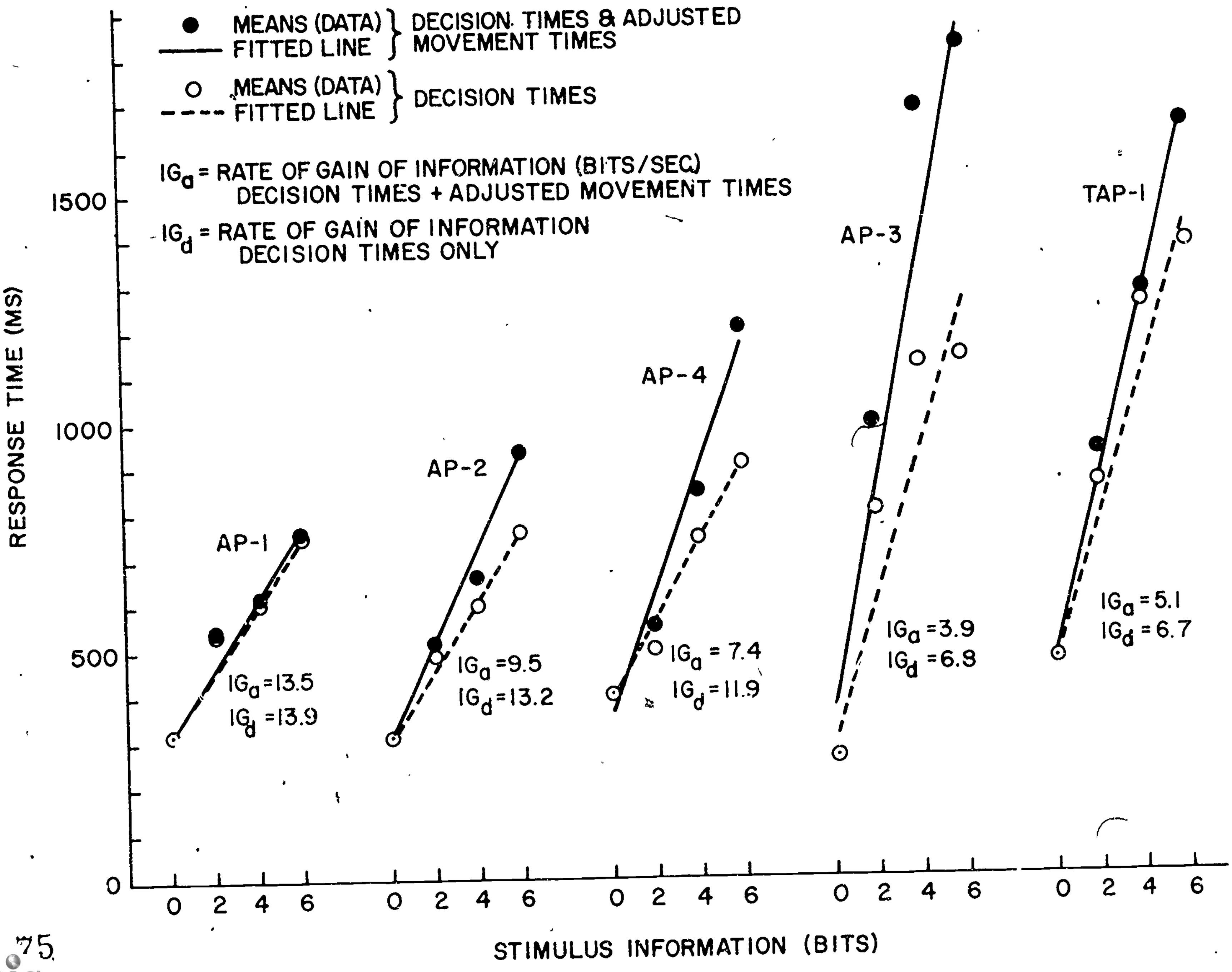

MEANS (DATA) } DECISION TIMES & ADJUSTED
FITTED LINE } MOVEMENT TIMES
MEANS (DATA) } DECISION TIMES
FITTED LINE
IG_a = RATE OF GAIN OF INFORMATION (BITS/SEC)
DECISION TIMES + ADJUSTED MOVEMENT TIMES
IG_d = RATE OF GAIN OF INFORMATION
DECISION TIMES ONLY
RESPONSE TIME (MS)
1500
1000
500
0
AP-1
IG_a=13.5
IG_d=13.9
AP-2
IG_a=9.5
IG_d=13.2
AP-4
IG_a = 7.4
IG_d = 11.9
AP-3
IG_a = 3.9
IG_d = 6.8
TAP-1
IG_a = 5.1
IG_d = 6.7
0 2 4 6
STIMULUS INFORMATION (BITS)

FIGURE 10.

-70-

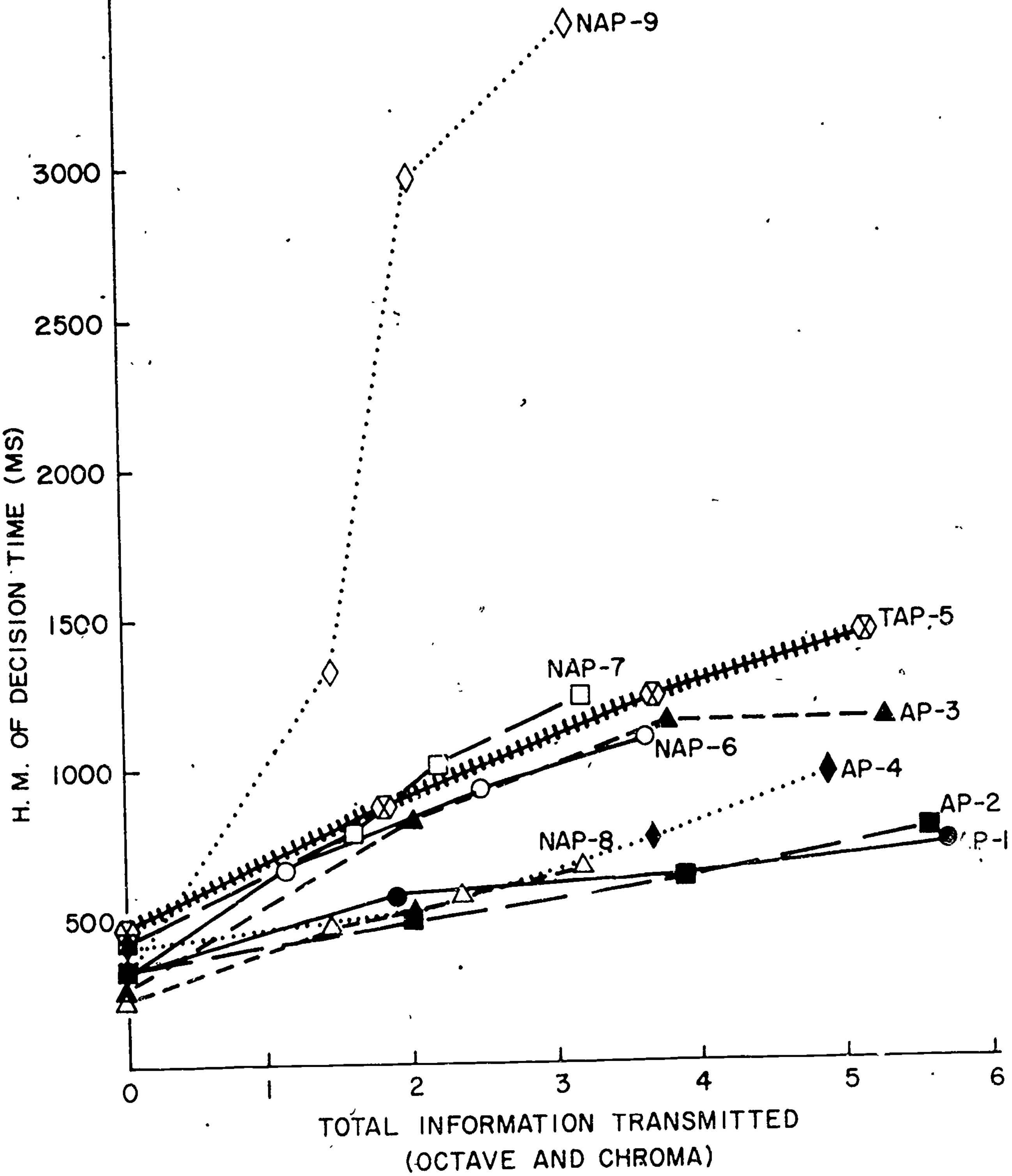

NAP-9
NAP-7
TAP-5
AP-3
NAP-6
AP-4
AP-2
NAP-8
3000
2500
2000
1500
1000
500
H. M. OF DECISION TIME (MS)
0
1
2
3
4
5
6
TOTAL INFORMATION TRANSMITTED
(OCTAVE AND CHROMA)

FIGURE 11.