Distinctiveness and serial position effects in tonal sequences

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The proportion-of-the-total-duration rule (Kidd & Watson, 1992) states that the detectability of a change in a component of a tonal sequence can be predicted by the proportional duration of the changed component relative to the length of the sequence as a whole. A similar viewpoint relies on temporal distinctiveness to account for primacy, recency, and other serial position effects in memory (Murdock, 1960; Neath, 1993a, 1993b). Such distinctiveness models predict that an item will be remembered if it is more distinctive along some dimension relative to possible competitors. Three experiments explored the relation between distinctiveness and proportional duration by examining the effects of the proportion of the total duration of a tone in a sequence, serial position, and interstimulus interval (ISI) on the detection of a change in one component of a tonal sequence. Experiment 1 replicated the basic effect with relatively untrained subjects and a fixed frequency difference. Experiment 2 showed that distinctiveness holds for tonal sequences and a same/different task. Experiment 3 combined the two to show that proportional duration, ISI, and position of the changed tone all contribute to discrimination performance. The present research combines theories that have been proposed in the psychophysics and memory fields and suggests that a comprehensive principle based on relative distinctiveness may be able to account for both perceptual and memory effects.

Memory for a percept must, in some sense, be dependent on the original sensory processing of that event. Indeed, some theorists go so far as to make no particular division between perception and memory and suggest that memory is simply the residue of the prior processing of a stimulus (Crowder, 1993). It should not be surprising, therefore, to find that researchers of perception and of memory observe similar patterns of data and propose similar rules to describe human performance.

The present experiments explore the similarities and differences between two accounts of temporal effects reported in the perception and memory literatures: the proportion-of-total duration (PTD) rule (Kidd & Watson, 1992; Watson, Foyle, & Kidd, 1990) and distinctiveness models based on Murdock's (1960) model (Neath, 1993a, 1993b). Each of these views offers a simple principle, based in part on Weber's law, that describes the effect of manipulating temporal components—the duration of a stimulus in the former case and the presentation sequence in the latter.

The Proportion-of-the-Total-Duration Rule

Numerous psychophysical studies have investigated the ability of humans to discriminate changes in the fre-

quency of acoustic stimuli. Human observers can detect a change in frequency of about 3% for frequencies up to about 1000 Hz (Harris, 1952) and can, in some cases, detect as little as a 0.2% change (Wier, Jesteadt, & Green, 1977). However, when the stimuli become more complex by the addition of context tones before and after the target, discrimination thresholds for a single target within a multi-tone sequence fall dramatically, often with a 20%–30% change or more being needed for consistent discrimination (Spiegel & Watson, 1981). This effect has led some researchers to suggest that the more complex a stimulus, the more its processing is determined by central rather than peripheral mechanisms (Watson & Kelly, 1981). The elevation in thresholds due to a more complex stimulus has been termed *informational masking* (Pollack, 1975; Watson, 1987). Results from studies that have used 9- or 10-tone equal-length stimulus components consisting of tones randomly chosen from the frequency range within which most speech information falls (300–3000 Hz) are consistent with the idea that informational masking may impose a limit on performance (Spiegel & Watson, 1981; Watson, Kelly, & Wroton, 1976; Watson, Wroton, Kelly, & Benbasset, 1975).

Watson et al. (1990) presented sequences of pure tones in a frequency discrimination task and found a strong relationship between the number of components in a tonal sequence and the threshold for discriminating one component within a sequence. Significant increases in threshold occurred when the sequences exceeded seven elements. Neither the total duration of the sequence nor the identity of the components within the sequence had a substantial

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effect on thresholds. Watson et al. (1990) originally interpreted this result as reflecting a limit on the informational capacity of immediate auditory memory. They suggested that the capacity of the auditory processor might be limited by the number of acoustical components (or the amount of information) that can be held in immediate memory. This strong dependence on the amount of information that can be successfully retained is similar to Miller's (1956) magical number 7 ± 2 , which was supposed to represent the limitations on immediate memory.

Although, at first glance, there appeared to be an absolute limit on the number of tones that could be held in auditory memory, Watson et al. (1990) suggested that the data might be better described by a relative limit. They noted that in their experiments, the target-tone duration was always equal to the total duration of the pattern divided by the number of components. As more components were added, the proportion of the total pattern duration occupied by the target tone decreased. Rather than concluding that the limit in performance was due to the *number* of tones, Watson et al. (1990) suggested that the *proportion of the total duration* of the entire sequence occupied by the target tone was the critical factor in determining the threshold for the discrimination of the stimulus.

Kidd and Watson (1992) tested this hypothesis by varying the number of components in a tonal sequence and the proportion of the total sequence occupied by the target tone separately. Rather than changing all the tones equally as the number of components was varied, target-tone durations were set at one of three proportions of the total duration. Kidd and Watson found that over a wide variety of absolute durations and number of components, although there was a small effect of total pattern duration, the critical variable in determining threshold for frequency discrimination was the proportion of the duration of the total sequence taken up by the target tone. The larger the proportional duration of the target tone, the lower the threshold.

The PTD rule states that "each individual component of an unfamiliar sequence of tones is resolved with an accuracy that is a function of its proportion of the total duration of the sequence" (Kidd & Watson, 1992, p. 3109). In its most simple form, the rule assumes that attention is allocated across all tones equally. This assumption, as they acknowledged, was qualified by an increase in discrimination for the final item in a tonal sequence (Kidd & Watson, 1992) and by the observation of both recency and primacy effects with discrimination of tonal sequences (Cacace, McFarland, Emrich, & Haller, 1992; McFarland & Cacace, 1992).

Distinctiveness Models

Early theories of short-term memory suggested that there was an informational limit on the number of items (later termed "chunks") that could successfully be held in short-term memory (e.g., Miller, 1956). Many current theories still apply an absolute limit, although this is now usually expressed as a temporal limit rather than an item limit (e.g., Cowan, 1995; Page & Norris, 1998). For ex-

ample, the articulatory loop component of Baddeley's (1986) working memory holds approximately 2-sec worth of speech information. The key prediction of all these views is that the longer an item has to be held in memory, the worse memory will be, assuming there is no opportunity for rehearsal (see Capaldi & Neath, 1995, for a review).

In contrast, distinctiveness theories (Glenberg & Swanson, 1986; Murdock, 1960; Neath, 1993b; Neath & Crowder, 1990) allow for improvements in performance with the passage of time because temporal effects are viewed as relative rather than absolute. Historically related to ideas developed by the Gestalt psychologists (see Murray, 1995), these distinctiveness models propose that the distinctiveness of each item can be calculated by summing its psychological distance from every other item from which it needs to be discriminated. Because the materials in most memory experiments are controlled for differences on most dimensions (such as familiarity, imageability, etc.), the only dimension that can be used to discriminate among them is the position or the time of presentation. In Murdock's formulation, the relevant dimension for lists of items was position; Neath's (1993b) version substituted time.

A variety of distinctiveness models have been used to account for results from a large range of tasks, such as free recall (Baddeley, 1976; Baddeley & Hitch, 1993; Glenberg & Swanson, 1986; Neath & Crowder, 1990), serial recall (G. J. Johnson, 1991; Murdock, 1960; Neath & Crowder, 1996), recognition memory (Neath, 1993b), and perceptual identification (Murdock, 1960). In addition, these models have been applied over a variety of absolute presentation times from less than a second (Neath & Crowder, 1996) to over a minute (Neath & Knodler, 1994).

One interesting prediction of distinctiveness models is that memory can actually improve over time if the relative distinctiveness of an item increases. In particular, they predict that immediately after a list is presented, the final item is so distinctive that it overwhelms the other items, resulting in a strong recency effect. However, as the retention interval increases, the final item loses proportionally more distinctiveness than the first item, leading to an absolute increase in performance on the first item and to a decrease in the final item. Traditional models of short-term memory, such as Baddeley's (1986) working memory, have no trouble explaining the decrease in recency over time but have a difficult time explaining an absolute increase in memory for the first item with an increase in the time before test.

The PTD rule might be considered a version of a distinctiveness model. The detectability of a change in a stimulus is not related to the absolute duration of the stimulus, but to its relative length when compared with the other stimuli in the set. The present experiments explore the similarities and differences between the PTD rule and distinctiveness models of memory.

In the experiments that follow, subjects were presented with two sequences of five tones and were asked to decide whether the sequences were exactly the same or whether one tone was higher or lower in pitch than the

corresponding tone in the first sequence. Experiment 1 was meant to be a replication and extension of Kidd and Watson (1992) to determine whether the PTD rule would hold with relatively untrained subjects and a constant frequency difference. In Experiment 2, the interval between the two sequences of tones was varied, and discrimination performance at each serial position was measured to determine whether larger intervals result in better performance on the first item and in worse performance on the final item (as is predicted by distinctiveness models). Experiment 3 explored the interaction of serial position, interstimulus interval (ISI), and the PTD rule.

EXPERIMENT 1

In Experiment 1, subjects were presented with two sequences of five tones and were asked to determine whether the sequences were the same or different. On *different* trials, the tone was increased or decreased by a constant 18%. In five conditions, the PTD occupied by the target tone as well as the absolute duration of the sequence were varied. The PTD rule predicts that the critical factor in discrimination performance is the ratio of the duration of the target tone to the duration of the entire sequence—that is, the larger that number, the better the performance. The experiment was designed to be a replication of Kidd and Watson (1992) and to determine whether that effect still obtains with relatively untrained subjects and a fixed frequency difference.

Method

Subjects. Thirty-two undergraduate students at Purdue University participated in this study in exchange for course credit.

Apparatus and Stimuli. A set of 50 pure tones ranging from 300 to 2593 Hz were generated by increasing each tone's frequency by 4.5%. These tones were separated into five blocks of 10 tones. Five-tone sequences were generated by randomly choosing one tone from each block, with the constraint that adjacent frequencies could not fall within 4.5%. Each tone had a 5-msec rise and decay envelope. The changed tone increased or decreased in frequency by

18%, with the constraint that no change could produce a tone that was already in the sequence or was outside of the frequency range of the pattern. For each trial, two tonal sequences, separated by 500 msec, were presented over headphones at approximately 75 dB sound pressure level by an Apple Macintosh LC computer interfaced with a Sony amplifier. Responses were collected via a mouse: The subjects clicked on an icon marked "same" if they thought the sequences were the same and on an icon marked "different" if they thought the sequences were different. Half of the sequences were exactly the same and half differed by 1 tone. Of the *different* stimuli, half of the changes were made by increasing the frequency, and half were made by decreasing the frequency.

The five experimental conditions are displayed in Figure 1. To the right of the description of the duration of each tone is a rectangle representing the sequence of tones for that condition. Each subdivision represents the relative duration of each tone within the sequence, and the dark bar is the target tone. The tonal sequences ranged in total duration from 750 to 2,250 msec. The target tone, which was always the middle tone, ranged from 125 to 500 msec, with three of the conditions having target tones that were identical in absolute length (250 msec). In the first two conditions, the PTD of the sequence occupied by the target tone was .33 but each sequence had different absolute lengths (750 and 1,500 msec, respectively). The target tone in the third condition had a proportional duration of .20, with all the tones in the sequence being the same length (250 msec). The target tones in the final two conditions had proportional durations of .11, with the total duration of the sequence varying between the conditions (250 and 125 msec, respectively). Note that, in three of the conditions (1, 3, and 4), the duration of the target tone was identical. The PTD rule predicts that, regardless of the absolute duration of the target tone or of the entire sequence, proportional duration will be the main factor in discrimination performance, with larger proportional durations of the target tone resulting in better performance.

Each subject received 100 trials in each of the five conditions. The trials were mixed together in a new random order for each subject. Thus, the subjects did not know which condition they would hear on any given trial.

Procedure. The subjects were told that they would be presented with two sequences of five pure tones separated by a pause. Their task was to determine whether the two sequences were exactly the same or whether one tone in the second sequence was different and to use the mouse to click on the icon corresponding to their response. They were informed that half of the sequences would be exactly the same and that half of the sequences would have a different tone in the second sequence. The subjects were told that the changed stim-

Figure 1. Stimuli used in Experiment 1. Each box represents one pure tone (in the range of 300–3000 Hz) in the sequence, with the target tone in bold. PTD is the proportion of the total duration of the sequence occupied by the target tone.

ulus would always be the middle tone and that the frequency of that tone could be either higher or lower than in the first sequence. They were also informed that the duration of the tonal sequences would vary randomly throughout the experiment. The subjects responded by using the computer mouse to click on an icon labeled "same" if they thought the sequences were the same and on an icon labeled "different" if they thought the sequences were different. All the subjects exhibited familiarity with using the mouse and were given two practice trials in order to allow them to become comfortable with the procedure.

The subjects were given the opportunity to take a break after every 100 trials.

Results and Discussion

Analyses were conducted using same-different d' (differentiating model; Macmillan & Creelman, 1991) based on the hits and false alarms from the 100 trials in each condition for each subject. Mean d' averaged across subjects for the five conditions are presented in Figure 2. The error bars represent the standard error of the mean. Performance ranged from d' 's of over 4 for the two .33 conditions (4.20 and 4.43, respectively, for the two left bars) to less than 2 for the two .11 conditions (1.80 and 1.63, respectively, for the two right bars), with the .20 condition (3.14, middle bar) falling in between. This experiment replicates Kidd and Watson (1992), with better discrimination for greater proportional duration of the target tone. Note that the total duration of the sequences doubled within a condition but that discriminability of the target tone remained the same. In addition, in three of the conditions, the target tone was exactly the same absolute length (250 msec), and only the proportional duration of the stimulus differed among those conditions. Neither the absolute length of the stimulus nor the absolute length of the target made an important difference. The critical variable was the PTD occupied by the target tone.

An analysis of variance (ANOVA) performed on the individual d' data confirms what is evident in Figure 2:

There was a main effect of proportional duration, with the larger proportional durations resulting in better performance [$F(1,4) = 40.29, MS_e = 1.37, p < .01$]. Post hoc tests (LSD test) showed no difference between the two .33 conditions ($p = .53$), no difference between the two .11 conditions ($p = .55$), and reliable differences in every other comparison (all p 's less than .01).

This experiment replicated Kidd and Watson (1992) with untrained listeners, many fewer trials, and d' as a dependent variable instead of threshold. Although discrimination performance, on the whole, was much poorer than in the Kidd and Watson study, the basic proportional duration effect was still evident: Performance was almost entirely dependent on how long the target tone was in proportion to the total duration of the tonal sequence.

EXPERIMENT 2

Experiment 2 was designed to explore distinctiveness with tonal sequences. Although the size of the primacy and recency effects are usually considerably smaller with tonal stimuli than with verbal stimuli (Surprenant, Pitt, & Crowder, 1993), serial position effects have been found with frequency discrimination in tonal sequences. For example, McFarland and Cacace (1992) and Cacace et al. (1992) varied the serial position of a changed item in a three-interval forced choice paradigm and found robust primacy and recency effects with sequences of pure tones varying from 7 to 14 components. This is in contrast to Watson et al.'s (1975) finding of a recency effect only with same/different discrimination. Thus, there is some uncertainty over whether there is an effect of position within a tonal sequence that mimics serial position effects in verbal memory paradigms.

In Experiment 2, the interval between two sequences of tones was manipulated in an effort to determine the ef-

Figure 2. Values of d' as a function of proportional duration (PTD) and total duration of the sequence. Error bars are the standard error of the mean for each condition.

fect of this interval on the serial position effect with tonal sequences. Distinctiveness models predict that, as the retention interval increases, performance on the final item will decrease but, at the same time, performance on the first item will increase. This is because, as the interval increases, the distinctiveness of the final item decreases relative to the other items in the list, and the first item becomes more discriminable.

In this experiment, the to-be-changed tone occurred in each serial position while proportional duration was held constant—similar to the way in which most memory experiments are conducted. In addition, the interval between the tonal sequences was varied from 500 to 2,000 msec in order to assess the effect of ISI. This experiment was designed to determine whether distinctiveness can predict performance on a frequency discrimination task.

Method

Subjects. Sixty-four Purdue University undergraduate students participated in this study in exchange for course credit. The subjects were randomly assigned to one of the two delay conditions.

Apparatus and Stimuli. The tonal sequences were generated according to the same algorithm as in the third condition (all tones equal length) of Experiment 1 (see Figure 1). ISI (500 or 200 msec) was manipulated between subjects so that each ISI condition consisted of data from 32 subjects. Each subject was given a total of 200 trials, with half of the trials being *same* and half being *different*. Of the 100 *different* trials, each subject was given 20 trials at each of the five serial positions. Which tone changed on any particular trial was randomized so that the subject was not able to predict which would be the changed tone. On *different* trials, the frequency of the changed tone increased in half of the trials and decreased in the other half of the trials.

The apparatus and response collection were the same as those in Experiment 1.

Procedure. The subjects were given the same instructions as in Experiment 1, except that they were told that the changed tone could occur at any of the positions. They were told that their task was to determine whether the two tonal sequences were the same or were different. They were informed that half of the sequences would be exactly the same and that half of the sequences would have a different tone somewhere in the second sequence. All the stimuli were presented and the responses collected using the same apparatus as that in Experiment 1.

The subjects were given a break halfway through the experiment.

Results and Discussion

Percentage correct was calculated from the 100 *different* trials (20 trials at each position) separately for each subject. The analyses are based on those data. Figure 3 shows proportion correct, averaged across subjects for each serial position at each ISI. The error bars represent the standard error of the mean. Mean squared errors on the percent correct data ranged from .03 to .04. Although overall performance was about the same in the two ISI conditions (about 60% correct for both), with increasing ISI, performance on the first item increased and performance on the final item decreased, as predicted by temporal distinctiveness. Although the design does not permit d' analyses at each serial position, overall d' was obtained by calculating total correct collapsed across serial position for each subject for *different* responses when

Figure 3. Proportion correct for each serial position as a function of interstimulus interval.

the stimuli were different (hits) and for incorrect *different* responses when the stimuli were the same (false alarms). As the retention interval increased, overall false alarms rates increased from .23 to .29 for the 500 and 2,000 msec conditions, respectively. Overall d' was then calculated by using the differencing model described in Macmillan and Creelman (1991) for same-different designs. Overall d' was higher for the 500-msec ISI condition (2.08) than for the 2,000-msec ISI condition (1.74). This is a reliable difference [$F(1,62) = 5.02, MS_e = 0.41, p < .02$]. This result is not surprising, given that performance on most memory tasks decreases over time. However, it should be emphasized that, with an increase in ISI, discrimination performance on the first item actually increased. This result replicates those of studies performed with snowflakes, words, and sentences (Neath, 1993b; Neath & Knodler, 1994), and those that have varied presentation times of a list from less than 1 sec to 20 sec (Neath, 1993b; Neath & Crowder, 1996).

An ANOVA confirmed the above observations: There was no main effect of ISI [$F(1,62) < 1, MS_e = 0.10, p = .95$], there was a reliable effect of serial position [$F(4,248) = 12.179, MS_e = 0.03, p < .05$], and there was a reliable interaction of ISI and serial position [$F(4,248) = 3.79, MS_e = 0.03, p < .05$].

The experiment showed that, by increasing the interval between the presentation of two tonal sequences, one can actually *increase* discrimination performance at the first serial position. The serial position data for this experiment replicate those found by Watson et al. (1975), especially for the 500-msec ISI condition. There is a fairly monotonic increase in performance from the first to the last position, with not much of a hint of a primacy effect. At the longer delay, however, the primacy effect seems to have appeared. This may explain the difference between Watson et al.'s (1975) data and those of McFarland and Cacace (1992), who found very substantial primacy using a 3-IFC procedure. With the 3-IFC procedure, the delay between the initial sequence and the comparison sequence

can be very long. With increasing delays, good performance switches from recency to primacy (Neath, 1993b; Wright, Santiago, Sands, Kendrick, & Cook, 1985).

EXPERIMENT 3

It was shown in Experiment 1 that Kidd and Watson's (1992) original effect of proportional total duration of tonal sequences can be easily replicated with a slightly different methodology and with relatively untrained listeners. Accuracy in detecting changes depended on the PTD occupied by the target tone, rather than on the actual length of the target tone or the sequence. It was shown in Experiment 2 that, as the interval between sequences increased, performance on the final item decreased while, simultaneously, performance on the initial items increased.

Distinctiveness models in general ignore the actual duration of each item in the list. The PTD rule was originally formulated to predict how well a change in one tone in a series could be discriminated depending on the relative duration of the item. Both views address discriminability issues, but at different levels. The purpose of Experiment 3 was to see if both proportional duration and distinctiveness effects obtain simultaneously. Proportional duration, ISI, and position were varied in order to explore the interaction of these two factors.

Method

Subjects. A total of 155 Purdue University undergraduates participated in this experiment in exchange for course credit. One subject was discarded because she reported some hearing loss when questioned. Four subjects' data were discarded when it was discovered that they responded "same" on every trial throughout the experiment. The discarded subject data were collected in three different conditions.

Apparatus and Stimuli. The target tone refers to the only tone that was changed between the two presentations of the sequence. All of the other tones were equal in length to each other. In this ex-

periment, there were three target-tone positions (1, 3, and 5) and three proportional durations (.33, .20, and .11). When position 3 was the target, the three durational conditions were the first (.33), third (.20), and fifth (.11) conditions described in Figure 1. For the other two position conditions, the middle tone was exchanged with the first or the fifth tone so that the target position reflected a PTD of .33, .20, or .11. The algorithm for generating the tonal sequences and the changed tone was the same as that in Experiment 1. ISI was varied to be either 500 or 2,000 msec. The changed tone occurred at positions 1, 3, or 5. The changed tone increased and decreased in frequency an equal number of times. All the stimuli were presented and the responses collected using the same apparatus as that in Experiment 1.

There were 25 subjects in each of six conditions. Each group of subjects was tested at one of two ISIs (500 or 2,000 msec), with a changed stimulus at only one of three possible positions (1, 3, or 5). Each subject listened to 96 pairs of sequences, one third from each duration condition (.11, .20, and .33), half of which were *same* and half of which were *different*. This resulted in 16 *same* and 16 *different* observations per subject per proportional duration.

Procedure. The subjects were told that they would hear two sequences of pure tones and that their task would be to determine whether the two sequences were exactly the same or whether one of the sequences was different from the other. The subjects were informed that the only tones that could change were the first, middle, or last tones (depending on which group they belonged to) and that the tones could go either up or down in pitch. On each trial, they were asked to indicate whether the sequences were the same or different by clicking on the appropriate icon on the screen via the mouse.

The subjects were given a break halfway through the experiment.

Results and Discussion

Figure 4 shows average d' collapsed across subjects for positions 1, 3, and 5 as a function of proportional duration and ISI. The error bars reflect the standard error of the mean. Values of d' were calculated individually for each subject, using the same-different method (differencing model) described by Macmillan and Creelman (1991). A basic proportional duration effect was observed, with overall performance increasing from the left panel

Figure 4. Values of d' for three serial positions as a function of proportional duration (PTD) and interstimulus interval.

to the right panel. Position also had an effect, with the final position being better discriminated than the first, across all proportional durations. Finally, delay interacted with the position of the changed tone in the sequence, with the first item's being discriminated better at long ISIs than at short ISIs and the final position's being discriminated better at short ISIs than at long ISIs.

An ANOVA confirmed these observations. There was an overall main effect of proportional duration [$F(2,288) = 144.28, MS_e = 0.33, p < .01$], as well as of position of the changed tone [$F(2,144) = 37.33, MS_e = 1.48, p < .01$], but no main effect of delay [$F(1,144) < 1$]. However, there was a reliable interaction of delay and position [$F(2,144) = 3.91, MS_e = 1.48, p < .05$], indicating that delay had differential effects on discrimination performance across positions. Finally, there was a three-way interaction of proportional duration, delay, and position [$F(4,288) = 3.66, MS_e = 0.33, p < .01$], reflecting the smaller effect of delay when the proportional duration was .20.

One puzzling aspect of the data is the small size of the position $\times$ delay interaction in the proportional duration of the .20 condition. Although the effect is in the right direction, it is nowhere near the size of the interactions in the other two proportional duration conditions, nor is it comparable to the interaction in Experiment 2 (which used the same proportional duration). One disadvantage of using a fixed-frequency difference and a small number of trials is that the individual differences among subjects in their ability to discriminate one tone within a sequence of tones becomes much more prominent. These individual differences are remarkably large (D. M. Johnson, Watson, & Jensen, 1987) and are probably the cause of the slightly unstable data.

GENERAL DISCUSSION

Experiment 1 showed that proportional duration effects can be demonstrated with a fixed-frequency change, a relatively small number of trials, and untrained listeners. Experiment 2 showed that discrimination of the first item in a tonal sequence actually increases with an increasing interval between sequences. This replicates a number of experiments using probed recognition that have shown absolute increases in performance on the first item in a list with increasing ISI. Experiment 3 showed that serial position effects obtain even across varying proportional durations.

The data imply that relative duration is important in both memory and perceptual discrimination tasks. In particular, there is a sort of Weber's law relationship that suggests that *relative* duration or temporal discriminability is the important variable in discriminability and memory, not absolute duration. However, neither the PTD rule nor the distinctiveness models are process models, in the sense that they do not specify the process by which distinctiveness is determined. This relatively abstract principle could be instantiated in a number of different process models. For example, the OSCAR model (Brown, Preece, & Hulme, 2000) uses temporally based oscilla-

tors that are tuned to different cycles. Thus, OSCAR instantiates relative rather than absolute time, which is consistent with the central characteristic of both the proportional duration and the distinctiveness views.

There are a number of other theories that have explicitly included both perceptual and memory components and that could be adapted to include relative duration. For example, many theories have suggested that stimuli are encoded in different codes that have different characteristics in terms of duration and decay of the code. In a computational model originally designed to account for the perception of intensity information, Durlach and Braida (1969) used the term *sensory-trace coding* to refer to the process that holds a sensation in memory until it can be compared with another one. They assumed that the sensory trace tends to wander or otherwise be degraded as a function of time. They also proposed a second, more abstract type of memory coding that might affect the decision process. In the *context coding* memory process, a stimulus is immediately compared with the general context of sounds presented within the experiment. This mechanism is very sensitive to the range of intensities that must be compared, but it is assumed to be unaffected by the passage of time. The Durlach and Braida model explicitly relates resolution to both sensory and memory effects. This model assumes that the listener uses either mode alone or combines the two in an optimum fashion.

Similar dual-coding models include Fujisaki and Kawashima's (1970; see also Pisoni, 1973) auditory and phonetic codes, Crowder and Morton's (1969) precategorical acoustic store, and Nairne's (1990) feature model. In all of these theories, one code is more or less a veridical representation of the original stimulus containing modality-specific information, and the second code is some sort of postcategorical, abstract, and modality-independent representation. All of the dual-code theories predict that the sensory trace is fairly fragile, decaying rapidly over time or being overwritten by subsequent stimuli. The abstract codes are more durable and change less over time. Also, each of these theories (with the exception of the Fujisaki and Kawashima model) suggests that both codes are present from the initial encoding and that the listener uses whichever trace is the most useful for the particular task at hand.

Dual-code theories could be adapted to incorporate distinctiveness principles. For example, the decision rule in Nairne's (1990) feature model uses Luce's (1959) choice rule, in which the decayed memory traces are compared with all of the other items in the search set in order to determine which is the most similar. If there are fewer items in the search set, there is a higher probability of a match. Temporal distinctiveness could be included as part of the decision rule. Similar principles could be included in any of the dual-coding models.

Temporal factors in the discrimination of tonal sequences have been extensively explored by Sorkin and his colleagues (Sorkin, 1987, 1990; Sorkin & Montgomery, 1991; Sorkin, Montgomery, & Sadralodabai, 1994). Sorkin (1987) showed that varying the temporal pattern

of the to-be-discriminated pattern caused great disruption in a listener's ability to determine whether the tonal sequence had the same frequency pattern. In addition, he showed decreases in discrimination performance with increasing ISI between sequences, but only when the pair of sequences was identical in their temporal envelopes. Sorkin (1987) interpreted these data within the Durlach and Braida (1969) dual-mode model. He suggested that when the temporal envelopes were identical, processing was dominated by the trace mode. In contrast, when there was variability in the temporal envelope, the context mode was dominant.

Sadrulodabai and Sorkin (1999) showed that increases in the average duration of a gap in a tonal sequence have little effect on the attentional weight given to a particular tone, whereas an increase in the variance of the duration of the gap results in greater weight being applied to that tone. They explain this result using Lutfi's (1993, 1995; Lutfi & Doherty, 1994) component-relative entropy (CoRE) rule, which suggests that the critical factor in predicting discrimination is a component's relative contribution to the overall variance across all of the patterns in the experiment. The CoRE model focuses on variance across all the trials within an experiment. The PTD rule, on the other hand, does not explicitly address trial-to-trial variability but, instead, is focused on the structure of a single trial.

The present experiments show that both PTD and dimensional distinctiveness play a role in the discrimination of one tone within a tonal sequence. It is likely that the CoRE model can be extended to account for the results presented here, and perhaps a version of CoRE that takes into account standard memory paradigms could be a useful way of combining the ideas of proportional duration and dimensional distinctiveness.

Although the experiments reported here support the idea of relative as opposed to absolute time being an important factor in immediate auditory memory, Cowan, Sauls, and Nugent (1997) have argued that there is a role for absolute time as well. They showed a decrease in performance for single-tone discrimination over time even when the ratio of the retention interval between tones and the interpresentation interval between sets of tones were held constant. They argued that the concept of decay must be incorporated in any model of forgetting in auditory memory. However, in a recent reanalysis of his data, which took into consideration the temporal relationships between trials, Cowan, Sauls, and Nugent (2001) found little or no evidence of decay over time and has reversed the position taken in the Cowan et al. (1997) paper.

Regardless of the eventual generality of the PTD rule, it is interesting to see a parallel development of theories within two areas that see themselves as fairly independent. Although there has been a great deal of research on the relationship between perceptual and memory effects, most of it has concentrated on the psychophysical aspects of perception and memory (e.g., Baranski & Petru-

sic, 1992; Bradley & Vido, 1985) or on the relationship between imagery and perception (Finke, 1980, 1985; Shepard, 1984). Few studies have examined serial position effects and their relationship to discrimination (but see Cacace et al., 1992; McFarland & Cacace, 1992). None, until now, has varied the temporal relations among the to-be-discriminated items.

Temporal or variance factors have been identified as important factors in perception, memory, and learning (e.g., Gibbon & Balsam, 1981; Kidd & Watson, 1992; Lutfi, 1993; Murdock, 1960; Rickert & Robinson, 1993) and now are identified as being important factors in the discrimination of pitch in tonal sequences. These data imply that a single comprehensive theory of memory and perception could be developed, with both perceptual and memorial effects being dependent on the relative distinctiveness of items in a list or a sequence.

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