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Rate of Perceptual Processing *

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SUMMARY. The primary goal of Schulze and Schuster's (1977) experiment was to test Massaro's (1972) hypothesis that the rate of processing of the auditory image after the tone is turned off is equal to the rate of processing the stimulus code while the stimulus is present. The experiment was unsuccessful, however, since the authors did not take into account corresponding changes in the asymptote parameter of the model with changes in stimulus duration. This review discusses the problem in detail along with a general discussion of model testing and appropriate experimental procedure.

Auditory perception is not immediate but is a temporally extended process. One of the major goals of auditory-information processing research is to describe the dynamics of this process. In an extensive series of experiments, we have found that the backward recognition masking task is particularly suited to illuminate the temporal course of auditory perception. Observers are asked to identify a test sound which is followed by a masking stimulus. The results of these experiments consistently show that identification performance improves with increases in the stimulus onset asynchrony (SOA) between the test and masking sound. In experiments employing pure tone stimuli, the results have shown that

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the identification of pitch, timbre, loudness, spatial lateralization, and duration improves with increases in SOA asymptoting at about 250 ms. Similar results have been found with the identification of consonants and vowels in speech. For a review of this work, see Massaro (1975, Chapters 21-23) and recent experiments of Massaro et al. (1976) and Massaro and Idson (1976).

Hand in hand with this empirical work has been the development of a formal theory of auditory perception. It is assumed that perception of a tone occurs as a negatively accelerating growth function of processing time t. In the model, perception of a tone is characterized by the discriminability measure, D', of signal detection theory. Accordingly, performance can be described by

$$d' = \alpha(1-e^{-\theta t}) \quad (1)$$

where α is the asymptotic discriminability given unlimited processing time and θ is the rate of processing to this asymptote. It is assumed that processing time t includes both the duration of the tone and the following silent interval before the onset of the masking tone. In this case, t is equivalent to SOA.

In the model it is assumed that the value of α is independent of the value of θ. The asymptote α represents the potential information in the tone given unlimited processing time. Accordingly, α might change with changes in stimulus parameters such as the physical difference between the test alternatives in the task. The value of θ, on the other hand, may not necessarily change with changes in the stimulus parameters. One might expect θ to be more sensitive to process differences such as the degree to which the subject selectively attends to the identification task.

The question asked in Massaro's (1972) paper and Schulze and Schuster's paper is whether θ, the rate of processing, differs as a function of whether or not the test tone remains on for the processing interval. It is well-known that tone perception improves in tone duration. Short tones are heard as clicks and only take on a tonal quality with increases in duration. Massaro (1972, Experiment 1, Day 1) showed that the percentage of correct identifications of a test tone increased with increases in tone duration asymptoting somewhere between 40 and 60 ms. It should be stressed that processing time was asymptotic since no masking tone was presented. In terms of our model, it is clear that increases in tone duration increased α, the index of the potential information in the test stimulus. In order to test whether the rate of processing remains constant during the period of the tone itself and the silent interval afterward, both the test tone duration and the silent processing time were varied in a backward recognition masking task. In the silent condition, a 20-ms test tone was followed after a variable SOA by a masking tone. In the continuous condition, the test tone was left in for all but the last 10 ms of the SOA period.

The question was whether the rate of processing, θ, differed in the silent and continuous conditions. In order to answer this question, it was necessary to describe the results in terms of the model and to determine to what extent stimulus duration influenced α. The results from Day 1 had shown that increases in stimulus duration up to 40-60 ms increased α, whereas further increases had no further effect. Therefore, it was necessary to estimate a different value of α for each stimulus duration less than or equal to 40-60 ms. Stimulus durations beyond this value can be given the same value of α. In the backward masking experiment, the shortest test tone in the continuous processing condition was 40 ms whereas the test tone was 20 ms in the silent processing condition. It was assumed that α would not change with increases in tone duration beyond 40 ms. Therefore, a single estimate of α was sufficient for the continuous condition. Of course, a single estimate of α was also sufficient for the silent processing condition since only one test duration of 20 ms was presented. It should be noted that the fact that the shortest tone in the continuous processing condition was close to the minimal duration necessary for a maximal value of α made it convenient in that only one value had to be estimated in the continuous condition. If shorter tones had been used in the continuous condition, a single value of α would not have been sufficient but a different value of α would have had to be estimated for each tone duration shorter than the minimum necessary for a maximal value of α.

The model provided a reasonably good description of the data when the same value of θ was exployed in the silent and continuous processing conditions. Schulze and Schuster (1977) carried out a similar experiment but the tone durations that they employed were much shorter than those used in Massaro's (1972) experiment. In their analysis of the data, they did not allow for changes in α with increases in tone duration in the continuous processing condition. Accordingly, their results cannot be used to test the idea of whether the rate of processing during the stimulus itself differs from the rate of processing during the silent retroactive interval.

The observers in Schulze and Schuster's experiments identified a square wave tone as low or high. The test tone was presented continuously before presentation of the masking tone or was presented for 10 ms followed after a variable silent interval by the masking tone. The results are shown in Figures 1 and 2 of the paper. Schulze and Schuster varied the tone duration between 5 and 90 ms in their continuous processing condition. But in their description of the data in the continuous condition, only one value of α was estimated for all of the test tone durations. As noted above, however, α can increase with increases in tone duration. In other studies, I have shown that α increases with increases in tone duration out to 60-80 ms for pitch identification (Massaro, 1975, 449-451). Accordingly, given that most of the tones were less than this value in the Schulze and Schuster continuous condition, one cannot estimate the rate of processing because of the corresponding changes in α as test tone duration is increased. In order to test the model, tone durations greater than 60-80 ms must be employed. At first glance, Schulze and Schuster might respond that their subjects had already reached 100% correct at these durations and, therefore, a ceiling effect would preclude the effectiveness of this manipulation. However, one can decrease the difference in Hz between the low and high test tones so that performance does not reach a ceiling (cf. Massaro, 1975, p. 363). Given asymptotic performance at 85-90% correct, it would be possible to test the model against the observed data.

Schulze and Schuster (p. 270, Point 3) observe a logical problem in using Equation 1 to predict performance in the continuous processing and silent processing condition. Their criticism is based on the assumption that α is simply defined with respect to the experimental condition, continuous or silent, without concern for the durations of the test tones. However, α is directly related to tone duration, asymptoting at some duration beyond which further increases in tone duration do not change the value of α. Therefore, if the silent and continuous conditions happen to have the same test tone duration, α must be equivalent in the two conditions. In Massaro (1972, Experiment 1) the shortest tone in the continuous condition was 40 ms and it was assumed that further increases in test tone duration would not change α. Therefore, the continuous tone condition would be described by

$$d' = \alpha_{40}(1-e^{-\theta t}) \qquad (2)$$

What should be noted is that t in Equation 2 must be equal to or larger than 40 ms. If t were less than 40 ms, then α could no longer be equal to α_{40} since the test tone duration would be necessarily shorter than 40 ms. Accordingly, it may be helpful to specify Equation 1 as

$$d' = \alpha_{d}(1-e^{-\theta t}) \qquad (3)$$

where α_d is the asymptotic value for a test tone whose duration is equal to or greater than D; and t, the processing time, is therefore also equal to or greater than d.

With these preliminary remarks, let us turn to the difficulties in estimating the rate of processing in the silent and continuous conditions of Schulze and Schuster's experiment. Rate can be a fuzzy concept and it must be specified within a specific model in order to define it explicitly (Anderson, 1963). And once it is defined, one must be careful that estimates of rate are not erroneously influenced by changes in some other variable such as the performance asymptote. The problem with using their results to estimate rate of processing are the ceiling effects in the data. Subject 1 reached perfect performance in both the continuous and silent condition whereas Subject 2 obtained perfect performance in the continuous but not the silent condition. One cannot fit these data using our model since d' is undefined when the subject is performing perfectly and therefore no valid estimate of α can be obtained.

Schulze and Schuster bypass this problem by fitting a similar model to the percentage correct scores rather than the d' values. However, the rate of processing as defined in their model will change with changes in performance asymptote, regardless of the processing condition. If the stimulus conditions were altered so that the silent processing condition reached 100% correct at a shorter processing time than did the continuous condition, then a larger rate of processing for the silent than the continuous condition would be observed. The difference in Hz between the high and low tones could have been made larger in the silent than in the continuous condition. This example shows that the estimate of rate of processing can vary with the performance asymptote when performance is allowed to reach 100% correct. The ideal method for testing for different rates under the two conditions would be to adjust the difference between the low and high tones to give the same below-perfect-level of performance at maximal processing times in the two conditions. For example, the difference in Hz between the low and high tones could have been adjusted independently in the silent and continuous conditions so that performance asymptoted at 85% correct in both conditions at a 500 ms processing time interval. Since tone duration increases α, it would be expected that a much smaller difference in Hz would be needed for the continuous than for the silent processing condition. However, now the experimenter could directly observe any differences in rate without dependence on a model that corrects for differences in asymptote.

This problem of equating for asymptotic level of performance is not unique to the current issue but pervades every area of experimental psychology (Massaro, 1975). In developmetal studies and clinical studies, for example, investigators are continuously faced with the problem of comparing different groups with large differences in asymptotic performance level.

Having found differences in rate of processing in the silent and continuous conditions, Schulze and Schuster (1977) would conclude that auditory perception differs from visual perception in this regard. In contrasting auditory and visual processing, they argue that "as long as the (visual) symbol is intense enough the duration of the presentation is of negligible importance for identifying the symbol. What matters is the delay of the masker (Haber & Nathanson, 1969)" (page 2). However, this conclusion is premature and, in fact, is contradicted by existing data. Eriksen and Eriksen (1971) pursued the issue in an experiment in which they presented subjects with three successive visual symbols to be identified. Each of the three symbols was presented at the same spatial location in the visual display. The question of interest was the amount of time subjects needed to identify the symbols. In the silent condition, presentation time was held constant at a very short duration--the minimal time to correctly identify the three symbols 90% of the time when they were presented at an interstimulus interval (ISI) of 350 ms. This time was between 2 and 9 ms for the different subjects. The remainder of the time between stimuli was made up of a blank dark fixation field. In the continuous condition the stimulus was left on throughout the processing interval. Accordingly, the two conditions (silent and continuous) can be compared directly as a function of processing time. In one case the stimulus stays on during the interval; in the other, the stimulus is turned off.

Performance improved with increases in processing time for both the continuous and silent processing conditions. In the silent condition, when the time between stimuli was filled with a blank interval, performance reached 90% correct at 250 ms ISI. That is, after a very short presentation of each symbol, subjects needed a 250-ms blank period before presentation of the next symbol in order to report the symbol correctly. In the continuous condition, however, when the time between stimuli was completely filled by presentation of the stimulus, only a 200-ms presentation time was necessary to reach perfect identification of all three symbols. These results show that the duration of the presentation itself is critical for identification. The question of interest, however, is whether duration influences the rate of processing. One might argue from the Eriksen and Eriksen data that rate is affected since the continuous curve reaches asymptote before the silent curve. However, as I have argued above, it is not reasonable to estimate rates when the asymptotic level of performance is perfect and no valid estimate of the theoretical symptote can be made. The question of whether the rate of processing during the visual stimulus itself differs from the rate during the retroactive period cannot be answered by Eriksen and Eriksen's experiment.

In summary, rate of processing must be explicitly defined in a model of performance and the valid application of the model is contingent on the appropriate experimental procedures. Schulze and Schuster tested the hypothesis that the rate of processing of the auditory image after the tone is turned off is equal to the rate of processing during the actual stimulus presentation. A valid estimate of rate of processing cannot be obtained, however, precluding a definitive test of the experimental question.

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