Switching attention between the ears to monitor tones*

NIGEL HARVEY and ANNE M. TREISMAN

Department of Experimental Psychology, Oxford University, Oxford, England

Alternating dichotic presentation of tones was compared with monaural presentation in two different perceptual tasks. When Ss were asked to detect higher frequency target tones in lists of six background tones, they missed less than 5%. However, when the presentation was fast (10/sec) and the tones alternated dichotically, Ss reported "hearing" only three or four tones. In two further experiments, Ss were asked to judge the number of tones or to report their spatial and temporal positions; these tasks were much less accurately performed, for the dichotic lists, than the target detection task. The differing effects of switching rate on these tasks are discussed in relation to the types of processing they require.

Treisman (1971) reported and reviewed experiments in which Ss were asked to recall a list of auditory speech items. Performance was worse when the items within a list were presented alternately to the two ears than when they were presented sequentially to one or both. Further examination of the limitation involved requires investigation of its functional site, generality, and mode of operation. A precise identification of the changes in task demands associated with appearance of the effect would also be desirable.

Functional Site of the Limitation

In Treisman's (1971) experiment, there was an interaction between rate and type of presentation but not between list length and type of presentation. This suggests that the limitation arises mainly during perceptual analysis rather than during storage or retrieval of the items. In the present experiment, this was tested by looking for the effect on a monitoring rather than a recall task.

Generality of the Limitation

The limitation may occur only when speech items are used as stimuli. The present experiment tested this by employing pure tones rather than auditory speech items in a paradigm otherwise similar to Treisman's (1971). If the perception of auditory speech and pure tones depend on the same mechanisms, the result may help to identify the level of perceptual analysis at which the limitation operates. Presence of the effect with both types of stimuli would indicate that it arises prior to speech recognition, whereas its presence only with speech signals would suggest that it occurs during speech recognition. Experiments by Lawson (1966) and Treisman and Riley (1969) lend some support to the latter possibility. They found that pure tones and changes of a speaker's voice were detected equally well in the attended and unattended channels. However,

Moray and Fee (1970) cast some doubt on Lawson's (1966) finding, in that they did find impaired detection of tones embedded in the unattended speech message when transients at the beginning and end of the tones were removed.

Some limitation to attention has also been found with simultaneous tones. Moray (1970) and Moray and Fitter¹ found limits in Ss' ability to monitor in parallel two sequences of tones for increments in either frequency or intensity. These limits may have been due mainly to frequency rather than to dichotic separation of the tone sequences, but Moray and Fitter also found that dichotic separation increased the difficulty of their frequency-separated tones relative to binaural presentation. However, there may be factors other than the attention division requirement which affect performance in both experimental and control conditions when stimuli are presented simultaneously. Firstly, binaural presentation may benefit from interaural summation of information, and so may not be an appropriate control when attention-sharing decrements are being sought. Secondly, there may be cross-channel inhibition with simultaneous dichotic presentation, as suggested by Sorkin, Pastore, and Pohlman (1971). They found a small decrement with two-channel compared to single-channel presentation, then two signals were presented at once, but little or no difference between single- and two-channel conditions on trials when no signal was present on the contralateral channel.

Changes in Task Demands Associated with Appearance of the Effect

There are also differences in the task demands in Moray's experiments compared to those with alternating presentation of stimuli. Moray's studies compared efficiency in responding to both of two simultaneous inputs with efficiency in responding to one of the two or to one presented alone. A decrement in the former condition could be associated with changes in three separate task demands. (1) doubling the amount of material to be processed, (2) simultaneous rather than

*This research was supported by the Medical Research Council.

successive presentation of items, and (3) the presentation of relevant material on two separate input channels rather than one. Taking as the control condition attention to a single message presented on one channel, effects of the first task demand could be isolated by doubling the input rate relative to the control message, but still using successive presentation on one channel; effects of the second by presenting two messages simultaneously on a single channel, each at half the rate of the control message; and effects of the third by presenting alternate items to alternate channels, using successive presentation at the same overall rate as the control message. This last condition tests how far attention can be divided or alternated between the channels themselves rather than between competing stimuli on those channels. It is possible, of course, that two or more of these task demands either contribute additively or interact in causing the difficulty of the standard two-channel simultaneous input task. The present experiment (like the earlier one with speech stimuli, Treisman, 1971) tests only the third.

Nature of Limitation with Alternating Stimuli

Evidence of an attentional limitation with tones in such stimulus conditions comes from an experiment by Axelrod, Guzy, and Diamond (1968). In order to match the perceived rates of alternating dichotic and successive monaural clicks, Ss required a faster actual rate for the dichotic clicks. Axelrod et al (1968) suggested that, at fast rates, Ss are unable to switch attention between the ears quickly enough and so lose a certain proportion of input clicks. We attempted to test this possibility in a slightly different task. If a certain proportion of stimuli fail to be analyzed, Ss should miss a certain proportion of target stimuli when monitoring for them in rapid alternating sequences. Alternatively, if they do attempt to follow the stimuli by switching attention, and if this requires a certain additional time, their response latencies should increase progressively through the list as they lag further and further behind. This prediction assumes that all stimuli are analyzed in the order in which they arrive, i.e., that they queue for attention in a buffer store. If stimuli can be dropped from the queue or taken out of order, response latencies should increase at first and then decrease as stimuli and attention get back into phase. This would produce oscillation of RTs with serial position.

EXPERIMENT I

Method

Apparatus and Stimuli

Pure sinusoids were generated by Advance Instruments J2-E oscillators and delivered to 1052 Sony DR-3C stereo earphones via a multichannel gate unit. Signals were gated at random. The

gate unit and recording and timing of responses were controlled by a LINC-8 computer. The frequencies of nontarget and target pulses were 1.000 and 1.050 Hz, respectively. Both had a duration of 80 msec and an intensity of 70 dB SL. Ss responded by pressing a button on a keyboard which was connected to the computer. RTs were measured from the start of the target tone.

Subjects

Five male and three female students, aged between 18 and 24 years, were paid for serving in one ½-h practice session and two experimental sessions of approximately 65 min duration each. All Ss were right-handed.

Experimental Design

Each trial consisted of a sequence of six pure sinusoids, either all of the same frequency (the nontarget 1,000 Hz) or else five of this frequency and one of another frequency (the target 1,050 Hz). Following each tone sequence, Ss were allowed a 2-sec intertrial interval (offset to onset) to make a response. In each block of 120 trials, target and nontarget trials were presented randomly with the constraint that each type of trial appeared equally often. Targets occurred equally often in each of the six positions in the tone chain. There were two rates, 10 tones/sec and 6 tones/sec, and two conditions, monaural and dichotic alternating. Speed and mode of presentation were constant within any one block. Prior to each monaural block, Ss were told whether the left or right ear would be stimulated. Prior to each alternating block, Ss were told whether the left or right ear would be stimulated first. There were eight blocks per experimental session. One experimental session was devoted to the fast rate and one to the slow rate of presentation. Order of presentation of dichotic and monaural blocks was balanced within each session for each S, whereas order of presentation of fast and slow blocks was balanced over sessions and Ss.

Procedure

Ss were instructed to press the key with their right index fingers as soon as they heard a target in the tone chain. If no target was presented, they were told to withhold their responses. They were requested to respond as fast as possible, while trying to keep their errors below five or six per block of 120 trials. The practice session consisted of 16 blocks of 20 trials each, given in the same order as the experimental blocks and with one speed of presentation following the other. During practice, Ss were given feedback regarding their reaction times and error rates. The two experimental sessions followed the practice session on separate days. Five additional practice trials were given before the start of each condition. Ss were given a 1-min break between blocks while data were stored on magnetic tape to be analyzed at the end of the session. In addition, they were allowed a 5-min break halfway through each session.

Results

Figure 1 gives the serial position curves for reaction times and percent omissions for each mode and rate of presentation. There were too few omissions and false positives to justify a statistical analysis over different serial positions. An analysis of the total omissions showed a significant effect only of dichotic vs monaural presentation [$F(1,7) = 36.6$, $p < .001$], as did an analysis of false positive responses [$F(1,7) = 6.54$, $p < .05$]. The effect of rate was not significant. Although the increases in omissions and false positives

were seen consistently across Ss, they occurred in extremely few lists, averaging only 1.8% for omissions and 0.8% for false positives.

A three-way analysis of variance on the reaction times showed that responses to dichotic lists were significantly slower than to monaural lists [$F(1,7) = 6.11, p < .05$]; the mean difference was 40 msec. The effect of presentation rate was not significant and neither was the interaction between these variables. The effect of serial position of the target in the tone chain was significant [$F(5,35) = 20.37, p < .001$], but there were no significant interactions of serial position with mode or with rate of presentation. A Newman-Keuls test showed that Position 1 gave significantly slower RTs than all the others ($p < .01$) and that Position 6 gave slower RTs than Positions 3, 4, and 5 ($p < .05$).

When Ss were asked for their comments on the task, they claimed that with the fast alternating lists they heard only three or four of the tones; they had the impression that these included the target whenever they responded to it.

Discussion

We look briefly at the serial position effects on RTs and then turn to the central question being investigated. There are two plausible reasons for the longer latency of responses to Position 1. One is a difference in Ss' state of expectancy. Their preparation may not have been maximal at the onset of the first tone, while the first tone itself could act as an additional warning signal for the rest of the list. Another reason, which would also explain the slower responses to Position 6, is that Ss made relative rather than absolute judgments of frequency, matching each tone to its predecessor and/or successor rather than to a memorized target. RTs to the first and last tones would then be delayed because they lacked a predecessor and a successor, respectively, so that less information was available on which to base the relative judgment.

The main aim of the experiment was to see whether rapid alternation between the ears caused perceptual difficulties with monitoring simple auditory stimuli, and whether such difficulties might be attributed to a limited rate of switching attention. The slight decrease in accuracy and increase in RTs for dichotic compared to monaural lists at both presentation rates suggests that alternating presentation does present some perceptual difficulty.

If this difficulty were due to a limited perceptual switching rate, what other predictions would follow? Various strategies could be available to Ss: (1) They might simply fail to process a proportion of the stimuli, as suggested by Axelrod et al (1968). The very small number of omissions (4% in the fast alternating lists) shows that this very rarely occurred. (2) They might hold the queue of stimuli in a fixed order to be dealt with serially at a slower attention-switching rate. This

Fig. 1. RTs and percent omissions in detecting target tones.

theory would predict increasing lag with increasing list position, so that the difference in RTs to alternating and monaural stimuli should increase with list position, as should the difference in RTs to fast and slow alternating stimuli. Neither of these predictions is borne out. The slight increase in missed signals and false positives with fast compared to slow alternating lists cannot have cancelled an alternative increase in RTs (through a change in speed-error tradeoff), since the main increase in missed targets was due to three Ss only, while the five Ss whose omissions remained constant (a mean increase of only 0.25%) also showed no increase in RTs on the fast lists. (3) Reversals of processing order might occur such that later stimuli received in phase with attention were analyzed before earlier ones waiting in the queue. However, unless the switching rate is very variable, this theory would predict much greater oscillations in RT with list position than we found, since the interval between stimuli in fast lists was 100 msec. (4) Ss might process first all the tones on one ear and then all those on the other ear. This theory is also ruled out by the data, since Ss would have to wait till the whole list had been presented to complete their monitoring of the first ear before switching to the second. If they had followed this strategy, RTs to target tones in Position 2 would have been delayed by at least 500 msec with fast lists and 830 msec with slow lists. In fact, RTs to the second tone in dichotic lists were only 2 and 34 msec slower than RTs to the second tone in monaural lists. Thus, none of the possible strategies associated with a limited switching rate appears to fit the results.

The only remaining explanation is that Ss are able,

Fig. 2. Number of tones reported in Experiment II.

with these simple stimuli at least, to "divide their attention" between the channels to monitor the frequency of all the tones, but that this in some way reduces their efficiency, so increasing RTs by 40 msec and false positives by about 2%. But this account raises a further question, namely how to reconcile it, together with the very high detection rates, with Ss' reports that they clearly heard only three or four tones in the fast alternating lists. Taken together, these findings suggest either that Ss in the fast alternating condition responded to tones which they did not subjectively "hear" or that targets were "heard" with a much higher probability than were nontargets. The former possibility is reminiscent of Fehrer and Raab's finding (1962) that simple RTs to visual stimuli show no delay in conditions in which the stimuli are masked by metacontrast from subsequent stimuli, and of Cumming's recent experiments (1971) showing the same for choice responses. However, Ss' introspections favor the latter possibility; they usually claimed that they heard the target when it received a manual response. The difference in the perception of target and nontarget items may therefore be more closely related to Neisser's finding (1964) that Ss cannot report the identity of background letters although they do detect the majority of target letters in a visual search task.

This paradoxical combination of Ss' assertion that they heard only three or four of the fast alternating tones with the fact that they detected almost all target tones seemed worthy of further investigation. We therefore decided to look more fully into Ss' perception of these fast alternating lists. Two further experiments were carried out in which Ss were asked to report how many tones they had heard.

EXPERIMENT II

Method

In order to explore further the nature of Ss' subjective

experience of the fast alternating lists used in Experiment I, we attempted to find monaural or dichotic lists which would sound perceptually equivalent to them. The Ss in Experiment I claimed that at the fast rate they often heard only three out of the six alternating tones, and that these occurred at regular intervals. In Experiment II, we therefore always presented three tones in Intervals 1, 3, and 5 within the framework of the six 100-msec intervals previously used for fast lists, and we added 1, 2, or 3 tones in the remaining three intervals. The aim was to see whether these tones disappeared subjectively and whether this depended on how many were presented. When one or two tones were added, their temporal positions varied from list to list. In all cases when presentation was dichotic, the tones within a list alternated between the ears. Ss were not told of these restrictions. The tones were all of the same frequency and duration as the nontarget tones in the previous experiment.

Eight right-handed undergraduate Ss each heard 30 monaural and 30 dichotic lists of Lengths 4, 5, and 6, and 10 lists of each type of Length 3. These were presented in two sessions, one monaural and one dichotic, with order counterbalanced across Ss. They were asked to listen to each list and immediately afterwards to mark in a response matrix a tick for each tone they had heard, showing the temporal and spatial position in which they had heard it. They were given matrices of 6 by 2 cells for the dichotic lists with left- and right-ear cells labeled, and matrices of 6 by 1 for the monaural lists. The order of writing their responses was not controlled.

Results

Figure 2 shows the averaged judged number of tones as a function of the presented number, together with the mean of the variances for individual Ss. Analysis of variance showed no significant effect of dichotic vs monaural presentation on the mean estimates of number, but a significant effect on the variances of individual Ss' means [$F(1,7) = 17.6, p < .01$]. Thus, although the reduction in perceived number with dichotic presentation failed to reach significance, Ss were considerably less accurate in judging the number of tones in dichotic lists.

Figure 3 shows, separately for dichotic lists which started on the right and the left ears, the total percentage of tones reported in each serial position, and how this percentage was divided between correct and incorrect ears. The peaks and troughs on alternate positions are due to the fact that two of the eight Ss filled some cells representing temporally simultaneous tones, although none were every presented. While the serial position curves for ear errors are relatively flat, those for omissions drop steeply on the last position: only about half the tones in Position 6 were reported. Ss made slightly less ear errors in lists which started on the left ear; otherwise, there were no systematic differences between the tones on the right and left ears, either in the probability of detection or of ear errors.

Ss were also much less accurate in judging the temporal positions of the tones and the gaps in the dichotic than in the monaural lists. The proportion of lists in which at least one error of temporal position was made was 71% for the dichotic lists compared to 29% for the monaural lists. (This difference was not due to errors in which tones were attributed to the wrong ear in dichotic lists, since ear errors were ignored in this

analysis.) Even for lists where the *number* of tones was judged correctly, Ss made many temporal position errors. For example, 60% of the correctly judged lists of four and five tones contained temporal position errors with dichotic presentation, while only 9% did with monaural presentation. Judgments of number were incorrect in 44% of the dichotic lists and 20% of the monaural ones. Thus, temporal judgments suffer more than judgments of *number* when presentation is dichotic rather than monaural.

Discussion

The variance of judgments made by our Ss was much greater with dichotic than with monaural presentation, although the mean judged numbers did not differ significantly. Our results with the lists of six tones differ from those of Axelrod et al (1968) in that their Ss showed considerably greater underestimation of the rate of tones in dichotic lists: the proportion D/M (dichotic heard number over monaural heard number) for our Ss on the lists of six was 0.93, while their Ss matched a rate of 16.8/sec dichotic to a monaural rate of 10/sec, giving a ratio M/D of 0.6. Guzy and Axelrod (1972) tested judged numerosity rather than rate, but only up to a rate of 8/sec, for which they found D/M = 0.81 for lists of six. However, as the variances indicate, it is unlikely that the difference reflects more *accurate* perception in our experiment. An alternative account is that range effects distorted the mean estimates in our experiment. Ss knew that the maximum number presented would be six and may have been biased towards filling in a certain proportion of sixes in the dichotic as well as the monaural lists.

Many of our lists contained temporal gaps which produced an objectively irregular rhythmic structure. We found that Ss were very bad at judging the presence and the temporal positions of these gaps. This finding is of some interest in relation to a theoretical issue raised by Axelrod et al's (1968) theory and by Axelrod (1972 personal communication); this is the question of what happens to the "missed" tones in fast regular sequences. Why do these unheard tones not leave temporal gaps in the perceived sequence, and so produce apparent arrhythmia? Our suggestion is that the temporal arrangement perceived depends on the *output* times of the perceptual mechanism rather than on the physical arrival times of the subset of stimuli that it is able to accept. On this hypothesis, if some of the stimuli queueing for the limited-capacity perceptual analyzers drop out through decay or displacement, their absence will not be detected by the S. The poor judgment of temporal patterns that we found with objectively arrhythmic sequences is consistent with this account.

EXPERIMENT III

In this experiment, we attempted to correct the

Fig. 3. Percent tones reported in lists of six as a function of ear and serial position.

possible source of bias introduced by the fixed response matrices used in Experiment II, and to separate the effects of rate and of number of tones presented. We also asked whether the results would vary with the form of response required, verbal or motor, since the different responses required might have induced a different choice of perceptual strategy in the two previous experiments. Guzy and Axelrod (1971) have shown that different response requirements can affect performance in this type of task, although the differences in their experiment appeared to be due to response rate ceilings rather than to changes in perceptual capacity. Half the Ss in Experiment III were asked to write down the number of tones they had heard and half were asked to tap out the number they had heard immediately after the list was presented.

Method

The experiment was divided into three sections: (i) In the first, 24 lists of six tones were presented at the fast rate used in Experiment I. Half began on the right and half on the left ear. Ss were not told that these lists would all be the same length. (ii) In the second section, 48 lists varying in length from three to eight tones were presented, all at the same fast rate as in Experiment I, and without gaps, so that the total duration of the lists varied from 300 to 800 msec for lists of three to eight tones, respectively. (iii) In the third section, the same lists as in Section ii were used again, but randomly interspersed with 60 lists in which the rate was varied irregularly as follows: the temporal positions of tones in the regular lists of eight were taken as a framework and two, three, or four were deleted. The remaining tones were made to alternate between the ears. The

Fig. 4. Number of tones reported in Experiment III.

actual patterns used are shown in Fig. 4 together with the results. Again, each S heard the tones both dichotically and monaurally, with the order counterbalanced across Ss. Sections i, ii, and iii were, however, given in this fixed order.

Four Ss, chosen randomly, verbally reported the number of tones heard and four were asked immediately after the list to tap a number of times which matched the number of tones they had heard. Two of the first four Ss gave unusual patterns of responses in that they underestimated the monaural lists much more than the dichotic ones. This pattern of responses had never occurred in the previous experiment, or in the informal reports in Experiment I. One of the two admitted that, with the dichotic lists, she had listened to one ear only and doubled the number she heard there. These two Ss were therefore replaced with two more, and their results are shown separately in Fig. 4.

Results

There was no systematic difference between the four Ss who responded verbally (after the two unusual Ss had been replaced) and the four who responded by tapping. This may be because the latter Ss verbally mediated their responses. Results from the two groups were subsequently pooled for further analyses. The mean estimates of number for the lists of six in Section i were 4.1 for the dichotic lists and 4.9 for the monaural. Both are appreciably lower than in Experiment II, supporting our belief that range effects introduced artifactually high judgments in that experiment. There were no systematic changes with practice over these 24 trials or across the same lists of six consecutive tones in any of the three sections.

Figure 4 shows the mean estimates of number for each type of list in Sections ii and iii and the means of individual variances. The dichotic lists gave lower estimates of number than the monaural lists (D/M for Section ii averaged 0.85). An analysis of variance on the lists without gaps from Sections ii and iii showed a significant effect of dichotic vs monaural presentation [$F(1,7) = 6.59, p < .05$] and also a significant interaction of this factor with the number of tones per

list [$F(5,35) = 4.58, p < .01$]. Again, Ss were much less accurate on the individual lists in the dichotic condition, as we see from the larger variances for these lists. The effect of monaural vs dichotic presentation on individual variances was significant [$F(1,7) = 8.01, p < .025$], and again this interacted with the number of tones [$F(5,35) = 3.16, p < .025$], showing that accuracy decreased more on dichotic than on monaural lists as list length increased.

An analysis of variance on the mean number judgments for the lists with 0, 1, or 2 gaps in Section iii also showed a significant effect of dichotic vs monaural presentation [$F(1,7) = 36.5, p < .001$], a significant effect of number of gaps [$F(2,14) = 8.32, p < .01$], and a significant effect of number of tones [$F(2,14) = 75.8, p < .001$]. In an analysis of the individual variances for the same lists in Section iii, the effect of monaural vs dichotic presentation and the effect of the number of gaps failed to reach significance, as did the interaction between these factors. Only the number of tones produced a significant effect [$F(2,14) = 8.19, p < .01$]. Thus, in these lists, dichotic presentation led to consistent underestimation, but not to increased variance relative to the monaural presentation.

Comparable lists were less accurately responded to in this experiment than in Experiment II. For the lists of six without gaps, the mean of the variances in the alternating condition was 0.58 compared to the previous 0.34. As pointed out earlier, range effects probably reduced the variance for these lists in Experiment II. However, Ss in Experiment II were also more accurate (though not significantly so) on three types of lists of four or five tones which happened to be the same in the two experiments and so could be directly compared; the mean of their variances was 0.35 in Experiment II compared to 0.49 in Experiment III. Accuracy on these lists was not affected by the range effect, since no S in Experiment III gave a judgment greater than 6 for any of

these lists. This finding is of some interest, since the responses required in Experiment II were much more complex (ear and temporal position had to be specified as well as number) and also took longer to make.

GENERAL DISCUSSION

Our findings clearly support the conclusion that rapidly alternating dichotic lists give rise to lower and less consistent estimates of number than do monaural ones, although they differ somewhat from those of Axelrod and his colleagues in the degree of underestimation of dichotic relative to monaural lists. Moreover, we have shown that Ss' accuracy is much lower when they are asked to report how many tones they heard than when they press a key on detecting a target tone. Ss can detect almost all target tones in lists in which they are unable to "hear" more than two-thirds of the tones. One reason may be that the former task involves memory storage; Ss can respond only *after* the whole list has been presented rather than immediately after a particular critical item has been detected. However, the more complex responses required in Experiment II actually produced, if anything, *more* accurate numerical judgments than the simpler responses of Experiment III. This suggests that the effects of delay and of response interference with memory are unlikely to have played much part.

A more plausible explanation is that the tasks of Experiments II and III are more demanding perceptually than that of Experiment I. The fact that these experiments also exaggerate the relative difficulty of dichotic compared to monaural lists suggests that the difference between dichotic and monaural presentation also affects primarily the perceptual level. How can one account for this difference? We will consider three possible explanations.

Cross-Channel Inhibition

It is possible that there are sequential inhibitory effects as well as the simultaneous inhibitory effects between the ears suggested by Sorkin et al (1971). Schubert and Parker (1955) found a decrease in the difficulty of understanding alternating speech when the contralateral ear simultaneously received a masking noise, and attributed this decrease to a reduction in a postulated "contralateral inhibitory off-effect." In physiological studies, Rozenzweig and Rosenblith (1953) and Barrett (1972) have shown sequential contralateral inhibitory effects in some cases extending up to 90-msec ISI. If the inhibitory effect were frequency-specific, it would account neatly for the relative absence of effect on target detections in Experiment I, since the target tones differed in frequency. However, we can probably reject this explanation on the grounds (1) that monotic backward masking effects are greater than dichotic ones (Elliott,

1962); (2) that backward masking effects typically decrease the duration and intensity of suprathreshold tones rather than making them disappear (Gold'dburt, 1961); (3) that, if masking did indeed eliminate some tones completely, this theory would predict perceived arrhythmia. An acceptable explanation should be compatible with the queueing plus drop-out hypothesis suggested earlier.

Processing Load

Our results are incompatible with the idea that perception is a unitary event with different tasks differing only at the response selection stage; rather, they agree with the view that perception consists of a number of distinct operations, not all of which are obligatory (cf. Laberge, 1971). The task demands in the present experiments differ for the detection and the number judgment experiments. Thus, we need to distinguish here at least three separate results of perceptual processing: (1) the detection of target tones, (2) numerical reports of the number of tones heard, and (3) conscious experience of "hearing the tones." We had hoped to make numerical reports depend on what was "heard" in Experiments II and III, but were probably not always successful. (An extreme example was the S who admitted listening to one ear in the dichotic condition and doubling the number she heard.)

Tones in the dichotic lists could differ along three dimensions: spatial location, time of occurrence, and frequency (target vs background), of which only the last was relevant to the detection task. One hypothesis is that conscious perception of the tones must follow a full analysis and requires S to specify and to recombine correctly the outputs of analysis along each of the three separate dimensions for each particular stimulus tone. Now, if this full analysis is impossible at the fast presentation rate, S would be unable to "hear" all the tones in the fast dichotic lists and unable to respond accurately when asked to count them or to give their temporal and spatial positions. On the other hand, a *detection* response could be triggered by the outputs of a single analyzer—in this case for frequency.

Does this account conflict with other results on multidimensional stimulus processing? Treisman (1969) reviewed findings suggesting that different analyzers can be used in parallel and that interference or difficulty in dividing attention arises chiefly when rapid or simultaneous stimuli compete for a *single* analyzer. The present suggestion that increased processing load impairs the fuller analysis required for conscious hearing seems inconsistent with this conclusion. However, it may be the recombination of the different analyzer outputs to produce a single integrated percept which is difficult or time-consuming rather than their parallel use.

The number of *monaurally* presented tones was also consistently underestimated by Ss in Experiments II and III, a finding which replicates those reviewed by White

(1963). However, White's explanation in terms of a limiting frequency of cortical excitability cycles cannot account for the greater degree of underestimation with dichotic presentation. In the present account, the explanation would be the same as for the dichotic tones, namely that at the fast rates, Ss are unable to analyze and to recombine all the attributes (such as frequency, temporal position, and duration) that must be specified before conscious perception can occur. The fact that their spatial location is constant reduces the difficulty of analyzing that attribute and so increases the number which can be consciously perceived.

How does this hypothesis explain the 40-msec increase in latency for dichotic lists in the detection task? Ss' observation that a detected target was usually among the three or four tones consciously heard suggests the following explanation: after detecting the target by its frequency, Ss in fact completed the analysis of its other properties before making their response. This took longer when the spatial location was variable.

Perceptual Switching

A difficulty for any theory which denies the reality of a switching limit is raised by a finding of Axelrod and Powazek (1972). They showed that the apparent rate of alternating clicks varied monotonically with their angular separation. This result is difficult to accommodate in a processing load account, which would presumably predict that the more discriminable the spatial locations of the stimuli, the easier they should be to process. Axelrod and Nakao² have shown a similar degree of apparent slowing with alternating tactile stimuli presented bimanually compared to unimanually. They suggest (following Kahneman, 1970) that a common limit to performance is set by the rate at which Ss can make an underlying motor change, such as a lateral eye movement or some other motor component of the orienting reflex. However, it is not entirely clear to us how such a motor process could help or hinder perception when clicks arrive over headphones, or why, if they do hinder the counting task, they should have much less effect on detections.

We concluded in discussing Experiment I that the concept of switching was incompatible with the results in the detection task. However, it could still be involved in other forms of perceptual processing. One major difference between the detection and the counting tasks was that the latter [like Treisman's (1971) verbal recall task with alternating digits] required a response to the list as a whole, while the former required a response only to one item within it. Therefore, the counting task may have forced Ss to send all the items through the same subsystem, while the detection task allowed the three on each ear to be processed separately and in parallel. For example, to tie this possibility more concretely to underlying neural mechanisms, the detection response might be triggered independently from either cerebral

hemisphere, while number judgments required all the tones to be processed by the same hemisphere. It is likely that tones reaching the same hemisphere from different ears or spatial locations will differ in neural pathway, quality, or latency, and thus require adjustments to be made for subsequent stages of processing. Switching time, on this hypothesis, becomes the time necessary to reset the parameters appropriately for the serial analysis of tones arriving from different sources. If this time is appreciable, processing will be delayed and items queueing for attention may be lost. In the *detection* task (for which this hypothesis assumes no switching is necessary), the increased latency for dichotic lists could be due simply to uncertainty about which hemisphere will, in fact, trigger the response. There were no differences between left- and right-ear latencies, but, since simple manual responses can be triggered for either hand from either hemisphere, these would not be expected.

Guzy and Axelrod (1971) attempted to test a similar idea by asking Ss to tap in synchrony with right-ear clicks using the right hand and with left-ear clicks using the left hand. They argued that this provision of independent response channels might eliminate the need to shift attention, but their results gave no evidence of a change in the form of preresponse processing. The difference between bimanual rates to monotic and dichotic clicks was as great as the difference between the corresponding unimanual rates. Their results could be taken as evidence against this account of the discrepancy between our detection and counting tasks, unless some factor in Guzy and Axelrod's experiment prevented their Ss' adopting a parallel mode of processing. For example, the fact that each S received randomly mixed trials on monotic and dichotic sequences, and the requirement to listen to the clicks for some time to get a clear estimate of rate before starting to respond, may have biased their Ss towards listening to the sequence as a whole rather than as two independent subsequences.

A difficulty for any spatial switching theory, including this one, is that it requires a separate explanation for the lesser, but consistent, underestimation of monaural clicks at fast presentation rates. The processing load hypothesis covers this finding within the same general account.

It might be possible to test these alternative accounts by using lists which alternated randomly rather than systematically between the ears, and comparing perception of tones which followed a tone on the *same* ear with perception of tones which followed a tone on the *other* ear. If the task required analysis of spatial location in both cases and if this were the main source of the difficulty produced by alternating tones, efficiency of perception should not differ for tones which followed a switch and for tones which did not. If some forms of switching or of contralateral inhibition were involved, however, perception should be worse on tones which followed a switch.

REFERENCES

- Axelrod, S., Guzy, L. T., & Diamond, I. T. Perceived rate of monotonic and dichotically alternating clicks. *Journal of the Acoustical Society of America*, 1968, 43, 51-55.
- Axelrod, S., & Powazek, M. Dependence of apparent rate of alternating clicks on azimuthal separation between sources. *Psychonomic Science*, 1972, 26, 217-218.
- Barrett, Y. W. Multiple use of the auditory cortex: Interaction at a single point. *Experimental Neurology*, 1972, 34, 1-15.
- Cumming, G. Visual perception and metacontrast at rapid input rates. Unpublished doctoral thesis, Oxford University, 1971.
- Elliott, L. L. Backward masking: Monotonic and dichotic conditions. *Journal of the Acoustical Society of America*, 1962, 34, 1108-1115.
- Fehrer, E., & Raab, D. Reaction time to stimuli masked by metacontrast. *Journal of Experimental Psychology*, 1962, 63, 143-147.
- Gold'cburt, S. N. Persistence of auditory processes within micro-intervals of time (new data on retroactive masking). *Biophysics*, 1961, 6, 76-81.
- Guzy, L. T., & Axelrod, S. Synchronization of unimanual and bimanual responses with monotonic and dichotic clicks. *Perception & Psychophysics*, 1971, 9, 161-164.
- Guzy, L. T., & Axelrod, S. Interaural attention shifting as response. *Journal of Experimental Psychology*, 1972, 95, 290-294.
- Kahneman, D. Remarks on attention control. *Acta Psychologica*, 1970, 33, 118-131.
- Laberge, D. On the processing of simple visual and auditory stimuli at distinct levels. *Perception & Psychophysics*, 1971, 9, 331-334.
- Lawson, E. Decisions concerning the rejected channel. *Quarterly Journal of Experimental Psychology*, 1966, 18, 260-265.
- Moray, N. Introductory experiments in auditory time sharing: Detection of intensity and frequency increments. *Journal of the Acoustical Society of America*, 1970, 47, 1071-1073.
- Moray, N., & Fee, M. Selective attention to pure tones and speech. *Psychonomic Science*, 1970, 18, 223-224.
- Neisser, U. Visual search. *Scientific American*, 1964, 210, 94-102.
- Rosenzweig, M. R., & Rosenblith, W. A. Responses to successive auditory stimuli at the cochlea and at the auditory cortex. *Psychological Monographs*, 1953, 67, Whole No. 363.
- Schubert, E. D., & Parker, C. D. Attention to Cherry's findings on switching speech between the two ears. *Journal of the Acoustical Society of America*, 1955, 27, 792-794.
- Sorkin, R. D., Pastore, R. E., & Pohlmann, L. D. Simultaneous two-channel signal detection. II. Correlated and uncorrelated signals. *Journal of the Acoustical Society of America*, 1971, 51, 1960-1965.
- Treisman, A. M. Strategies and models of selective attention. *Psychological Review*, 1969, 76, 282-299.
- Treisman, A. M. Shifting attention between the ears. *Quarterly Journal of Experimental Psychology*, 1971, 23, 157-167.
- Treisman, A. M., & Riley, J. G. A. Is selective attention selective perception or selective response? A further test. *Journal of Experimental Psychology*, 1969, 79, 27-34.
- White, C. T. Temporal numerosity and the psychological unit of duration. *Psychological Monographs*, 1963, 77, Whole No. 575.

NOTES

1. Moray, N., & Fitter, M. J. Attention and auditory processing: The detection of intensity increments during auditory time sharing. In preparation.
2. Axelrod, S., & Nakao, M. Apparent slowing of bimanually alternating pulse trains. In preparation.

(Received for publication October 25, 1972;
revision received March 15, 1973.)