Synchronization of unimanual and bimanual responses with monotic and dichotic clicks*

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In experiments requiring subjective judgments, the apparent rate of rapidly presented dichotically alternating clicks has consistently been shown to be slower than that of clicks presented monotically. The first of the present studies asked (1) if slowing of dichotic clicks would be observed when the listener's task was to "follow" the clicks with overt motor responses (unimanual keypresses) rather than to make psychophysical judgments, and (2) if following of dichotic clicks could be improved by providing two response channels (alternating bimanual presses). Both answers were affirmative. The second study asked (3) if the improvement obtained in the bimanual condition reflected increased perceptual capacity. The results indicated that it did not, but was attributable to an increase in response ceiling.

When a train of clicks is presented in which the click repetition rate is 5 to 40/second, the perceived rate is markedly slower if the clicks are delivered in alternation between the two ears (dichotically) than if they are delivered to one ear alone (monotically). At these repetition rates, the listener appears unable to shift attention rapidly enough back and forth between the ears to permit perception of all the presented clicks, so that the effective rate of dichotic clicks is substantially diminished. The apparent slowing of dichotic clicks has been observed in experiments using the psychophysical methods of limits and constant stimuli, in which Ss judged between successively presented monotic and dichotic trains, and in an experiment in which Ss estimated the rates in clicks/second (Axelrod & Guzy, 1968; Axelrod, Guzy, & Diamond, 1968).

In the work reported here, we asked (1) if the apparent partial loss from perception of dichotic clicks would be demonstrated with a procedure that does not rely either on comparisons between successively presented standard and comparison stimuli or on subjective estimates. The task chosen required

listeners to "shadow" or "follow" the presented clicks with a motor response; specifically, S attempted to synchronize manual telegraph-key presses with the clicks in a train. Our expectation was that, with Ss required to shadow clicks unimanually, fewer keypresses per unit of time would be elicited under conditions of dichotic alternation than under conditions of monotic stimulation at the same stimulus repetition rate. If this proved to be the case, it was then proposed to ask (2) if making two response channels available (one for each ear) would enable Ss to process the clicks from each ear separately from, and independently of, the clicks to the other ear, and thus to respond to dichotic clicks without interaural attentional shifts. Instructions to respond to dichotic clicks with one hand only would restrict the listener to a single output channel, necessitating interaural shifting; as indicated above, this should produce significantly poorer following than unimanual responding to monotic clicks. But, under dichotic stimulation, instructing S to respond to left-ear clicks with his left hand and to right-ear clicks with his right hand would provide two output channels and might allow independent processing of the clicks from the two ears. If such

independent processing is indeed possible, then dichotic clicks should be capable of being processed at a much faster rate than in the monotic-unimanual condition, which provides only one input channel and one output channel.

EXPERIMENT 1

Subjects

The Ss were 20 undergraduate men, 17-20 years old, without known hearing deficit or motor disability involving hand or finger mobility. Nineteen considered themselves right-handed and one, left-handed.

Procedure

On each trial, a train of clicks was delivered via one or two earphones of a headset. The S, seated at a table on which two telegraph keys were mounted, was instructed to listen to the click train until he felt confident that he could synchronize keypresses with the clicks, i.e., that he could follow the repetition rate with keypresses. The first response initiated a 3-sec test period during which the number of responses was recorded and at the end of which the click train was terminated.

The clicks were produced in Clevite "Brush" high-impedance crystal phones by 0.1-msec, 20-V pulses from Tektronix 161 pulse generators, which were triggered by a Tektronix 162 waveform generator. Pulses were monitored as to duration and amplitude with a Tektronix 360 oscilloscope, and as to rate with a Hickok DP-150 digital meter. The 3-sec test period was timed by a Grason-Stadler E1100H electronic timer, and responses were recorded on Grason-Stadler E3700 electromechanical counters.

Every S served under two conditions. These conditions were grouped on the basis of combination of stimulus and response mode into two sets, A and B (Table 1). In each set, there were two stimulus modes. In the *monotic* mode, the trains were presented to one ear, either the left or the right, and in the *dichotic* mode, to the two ears in alternation. In Set A, S was

Table 1
Experimental Conditions

Sets of Conditions*	Stimulus and Response Modes		
	Ear(s) Stimulated	Hand(s) Responding	Combination
A	Left	Left	Monotic Ipsilateral (MI)
	Right Alternating	Right Alternating	Dichotic Bimanual (DB)
B	Left	Preferred	Monotic Preferred (MP)
	Right Alternating	Preferred	Dichotic Preferred (DP)
C	Left	Alternating	Monotic Bimanual (MB)
	Right Alternating	Alternating	Dichotic Bimanual (DB)

*Experiment 1 included Sets A and B. Experiment 2 included Sets B and C.

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Fig. 1. Mean number of responses per second as a function of stimulus repetition rate, for each of the stimulus-response combinations in Experiment 1.

instructed to respond with his left hand to left-ear clicks, and with his right hand to right-ear clicks. When dichotic clicks were presented, he was to respond in bimanual alternation, pressing the left key for the left-ear clicks of the train and the right key for the right-ear clicks.

In Set B, the stimulus modes were the same as in Set A, but S was to respond to all trains with his preferred hand. A random half of the group received Set A first, followed by Set B; the other half received Set B first, followed by Set A.

Clicks were presented at repetition rates of 3, 7, and 9/second. Ten left-ear trials, 10 right-ear trials, and 20 alternating dichotic trials were given with each rate, for a total of 120 trials per set and 240 trials per S. The sequence of combinations of repetition rate and stimulus mode varied quasirandomly, with the following restrictions: (1) A given repetition rate did not occur twice in succession; (2) no more than two trials in the same stimulus mode occurred successively; (3) in each block of 12 trials, there were two alternating dichotic trials and two monotic trials (one left, one right) at each of the three stimulus repetition rates. An independent sequence was generated for each S. There was a break between the 60th and 61st trials of each set and a 10-min break between sets. The dependent variable was the mean number of responses made per second during the 3-sec test period. Before each set began, S received 6 to 12 monotic and dichotic practice trials at a slow repetition rate (1/second) to familiarize him with the task.

Results

Mean number of keypresses/second is

plotted as a function of stimulus repetition rate in Fig. 1; the parameter is combination of stimulus mode and response mode. Perfect following would have generated the line labeled "veridical."

Unimanual responding. With respect to our first question, the most appropriate comparisons are those between identical response conditions, i.e., dichotic preferred (DP) and monotic preferred (MP). For the two fastest stimulus rates, the answer is unequivocally affirmative: Ss shadowing clicks with their preferred hands made significantly fewer responses per unit time when the clicks were presented alternately to the two ears than when presented to one ear alone ($p < .001$).¹ The inferiority of the DP combination was remarkably consistent across Ss; this combination produced a lower number of responses than any other in 16 of the 20 Ss at 7/second and in 17 of the 20 Ss at 9/second.

The mean number of responses in the monotic ipsilateral (MI) combination was uniformly (though nonsignificantly) lower than in the MP combination. MI scores, of course, include nonpreferred hand responses, and the older literature on psychomotor capabilities would lead to the expectation that preferred-hand performance should be better than nonpreferred-hand performance (Bryan, 1892; Dresslar, 1892; Wells, 1908; see also Knights & Moule, 1967). When the MI data were analyzed according to hand (and ear), the mean for the monotic-preferred responses was higher than the mean for the monotic-nonpreferred responses at each of the three click rates. None of these mean differences was significant; as Table 2 shows, however, a significant proportion (15/20, $p < .03$) of the Ss did make fewer responses to ipsilateral 9/second clicks with their nonpreferred than with their preferred hands.

Bimanual responding. The answer to our second question is ambiguous. Following of dichotic clicks was significantly better with the bimanual (DB) than with the preferred-hand (DP) response mode ($p < .001$) for the two fastest rates, but failed to rise significantly above the levels attained with the best of the monotic unimanual combinations (MP).²

This failure might be accounted for in two ways. (1) The provision of two response channels may indeed have permitted processing of dichotic clicks without diminution, *but only through the preresponse (perceptual) stages*, the limit on processing from stimulus through motor response having been set by Ss' inability to respond rapidly enough to keep up with the inputs. The implication would then be that bimanual response ceilings are the

Table 2
Number of Ss Making Fewer (Column 2) or More (Column 3) Responses With the Non-preferred Than With the Preferred Hand, and Ties (Column 4) in Experiment 1, Monotic-Ipsilateral Combination

(1) Repetition Rate	(2) NP < P	(3) NP > P	(4) NP = P	(5) Total
3/Sec	10	6	4	20
7/Sec	13	6	1	20
9/Sec	15*	5	0	20

* $p < .05$

same as preferred-hand response ceilings.³ (2) On the other hand, permitting bimanual responding might have had no effect on the processing stages prior to the motor response, but could simply have raised the response ceilings, allowing S to respond faster than under unimanual conditions to dichotic trains whose effective rates had already been diminished in the preresponse stages of processing. Comparison of unimanual and bimanual response rates to *monotic* clicks would appear capable of deciding between these two possibilities. If 1 is correct, then, assuming that provision of two response channels would have no effect on the preresponse processing of monotic clicks, bimanual following of monotic clicks (MB) should be approximately the same as preferred-hand following (MP). If 2 is correct, then the MB combination should produce significantly better following than MP. Experiment 2, therefore, included both an MP and an MB combination (Table 1).

EXPERIMENT 2

Subjects

The Ss were eight undergraduate men, 17-20 years old, with the same restrictions as in Experiment 1. None had participated in the previous experiment. All were right-handed.

Procedure

As in the first experiment, every S served under two conditions, these conditions being grouped into Sets B and C (Table 1). Instructions for Set B were the same as in Experiment 1. In Set C, the stimulus modes were the same as in Set B, but S was to respond to all trains with bimanual alternation. A random half of the group received Set B first, followed by Set C; the other half received Set C first, followed by Set B. The repetition rates and the restrictions governing their presentation were the same as in Experiment 1.

Results

The results are presented in Fig. 2. Insofar as the combinations of stimulus

Fig. 2. Mean number of responses per second as a function of stimulus repetition rate, for each of the stimulus-response combinations in Experiment 2.

and response mode overlapped, the results of the two experiments were in good agreement. Responding was again significantly less in the DP combination ($p < .01$) for all comparisons, and bimanual responding to dichotic clicks (DB) was again not significantly different from unimanual responding to monotic clicks (MP).

Bimanual responding to monotic clicks. The differences of major interest were those between bimanual and preferred-hand responding to monotic clicks (MB vs MP). At each of the three stimulus rates, significantly more responses were made to monotic clicks with the two hands in alternation than with the preferred hand alone ($p < .01$ for 3 and 7/second and $p < .001$ for 9/second), which strongly suggests that the analogous increases, found in both experiments, in going from the DP to the DB combination were not due to an increase in prereponse processing, but rather to simple increases in Ss' ability to respond rapidly. That is, the faster responding in the dichotic bimanual than in the dichotic preferred combination does not reflect an attenuation of the apparent slowing of dichotic clicks. This conclusion is buttressed by the entries in the last two columns of Table 3, which indicate that the increases in responses/second from the preferred hand to the bimanual response mode were almost identical, at a given stimulus rate, for the two stimulus modes. The effect of providing the two response channels rather than one appears to have been to add a constant to the rate at which S responded, irrespective of whether the clicks were delivered to one ear or alternately to the

two. Corresponding values for Experiment 1 are also presented in Table 3. Although the absolute magnitudes of the differences were somewhat smaller than in Experiment 2, the percentage differences were similar across the two experiments.

DISCUSSION

The main results of the two experiments demonstrated that (1) an apparent slowing of dichotically alternating clicks could be revealed with a procedure which does not depend on subjective judgments, and that (2) providing two output channels in responding to dichotic clicks increased the ability to respond rapidly but probably did not affect the prereponse processing of dichotic clicks.

Quantitative Agreement with Previous Findings

In earlier reports, we have estimated the degree of apparent slowing of dichotic trains at various stimulus repetition rates (Axelrod et al, 1968; Axelrod & Guzy, 1968). Analogous estimates have been derived from the data of the present experiments, on the assumption that rates of responding to monotic and dichotic clicks are comparable indices of apparent stimulus rates if they are obtained under identical response modes. In Fig. 1, the monotic point of subjective equality (PSE)—the monotic click rate which would correspond perceptually to the apparent rate of a given dichotic rate (DR)—was obtained by dropping a perpendicular from the intersection of the MP curve and a horizontal drawn at the level of the obtained DP data point for that DR. When

Table 3
Amounts, in Responses/Second and Percentage, by Which Bimanual Responding was Greater Than Preferred-Hand Responding

Repetition Rate	Experiment 1		Experiment 2	
	Comparison		Comparison	
3/Sec	DB vs DP	0.34 (12)	DB vs DP	0.39 (13)
7/Sec	DB vs DP	1.06 (25)	DB vs DP	1.40 (25)
9/Sec	DB vs DP	1.52 (30)	DB vs DP	1.71 (28)

Note—Percentages, in parentheses, were derived by dividing the tabulated difference between bimanual and preferred-hand scores by the preferred-hand score.

necessary, the MP curve was arbitrarily taken to begin at the origin (0,0) of the figure. The same procedure was carried out with the DP and MP curves and with the DB and MB curves in Fig. 2. The PSEs are given in Table 4.

Also listed in Table 4 are the ratios PSE/DR. As to the meaning of the ratio, note that if there were no apparent slowing of dichotic clicks, then, for any DR, PSE = DR, and PSE/DR = 1. The more marked the apparent slowing, the lower would be the PSE, and the smaller the ratio PSE/DR.

In Fig. 3, PSE/DR has been plotted as a function of DR. The figure is a composite, the open circles representing the combined data of the three separate previous studies utilizing subjective judgments. The previously obtained ratios are close to unity at slow rates, decrease rapidly, and then remain level from about 7 to 40 clicks/second. The filled circles in Fig. 3 represent the mean PSE/DRs derived from

Fig. 3. The proportion PSE/DR as a function of DR. Open circles: values obtained in three previous studies (Axelrod & Guzy, 1968; Axelrod, Guzy, & Diamond, 1968). Filled circles: values based on preferred-hand combinations in Experiments 1 and 2. Filled triangles: values based on bimanual combinations in Experiment 2.

Table 4
Monotic PSE and PSE/DR for Each Dichotic Rate

Dichotic Rate (DR)	DP vs MP				DB vs MB	
	Monotic PSE		PSE/DR		Monotic PSE	PSE/DR
	Experiment 1	Experiment 2	Experiment 1	Experiment 2	Experiment 2	Experiment 2
3/Sec	3.00	2.83	1.00	0.94	2.82	0.94
7/Sec	5.20	5.06	0.74	0.72	5.56	0.79
9/Sec	6.42	6.24	0.71	0.69	6.84	0.76

the preferred-hand combinations in the present experiments, 1 and 2. The filled triangles represent the PSE/DRs derived from bimanual combinations in Experiment 2. Within the range of DR used in the present experiments, the results are in reasonably good agreement with the earlier ones, particularly when it is considered that the present data were obtained with a very different set of tasks from those used earlier.

Overproduction of Responses

One paradoxical aspect of the data requires some discussion. At the stimulus repetition rate of 3/second the dichotic and monotic bimanual combinations yielded significantly higher numbers of responses during the test period than the number of clicks delivered. The amount by which the mean number of responses exceeded "veridical" was about 0.2 to 0.4 responses/second (Figs. 1 and 2). Careful postexperimental checking of the test-period timer has ruled out the trivial explanation that the test period was 1/3 sec too long. A more likely interpretation lies in the intratrial timing of the responses relative to the timing of the clicks. Consider the generalized situation with k /second clicks, where k is close to the relative response ceiling. Recall that the S's first response will initiate the 3-sec test period, and assume that S, having heard the first few clicks of a train, is now set to begin responding to the next click. Call the time of onset of that click t_0 , and assume some finite reaction time to that click, RT_0 . The test period then runs from its start at $(t_0 + RT_0)$ to its finish at $(t_0 + RT_0 + 3 \text{ sec})$. Call the former time t_s ,

and the latter t_f . During the interval from t_0 to t_f , $3k + 1$ rather than $3k$ clicks will have been presented. If $RT_{3k+1} \geq RT_0$, and if S responds to every click, then during the 3 sec from t_s to t_f , $3k$ responses ("veridical") will have been recorded. But if for any reason $RT_{3k+1} < RT_0$, then $3k + 1$ responses will have been recorded over the 3 sec, for an average of 1/3 of a response per second more than "veridical."

It is easy to imagine how the latency of response to the last click might be shorter than that to the first. RT_0 seems a reaction time properly so called. But, because the clicks in the train were regularly and predictably spaced, it is conceivable and even likely that during the 3-sec interval, S came to anticipate clicks, i.e., to reduce the latency of his response. Indeed, there was nothing in the experimental situation to prevent him from reducing the latency to zero, that is, from responding simultaneously with the clicks, once he had established a rhythmic pattern of responding to the first few clicks in the train. The keypresses to the last few clicks would then have been perseverative responses to the predictable rhythm of the clicks, rather than specific responses each to a specific click.

In the absence of data on intratrial timing of clicks and responses, the foregoing interpretation of the overproduction is speculative, although such data could be obtained by continuous graphic or oscilloscopic recording. Whatever its interpretation, the overproduction has no bearing on the principal conclusions of these studies concerning the apparent slowing of dichotic clicks and the effects of providing

two output channels for the dichotic stimulus mode.

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NOTES

1. Except in testing mean deviations from veridical performance, p values to be reported here were derived from t tests, using the error mean squares of Treatments by Ss variance analyses, a separate analysis being performed for each repetition rate. Mean deviations from veridical were tested by t test against the hypothesis that the mean population deviation was zero. Values of $p > .05$ were taken to be nonsignificant.
2. The significant overproduction of responses (relative to "veridical"), observed with the DB combination at the 3/second stimulus rate, is dealt with below.
3. It would be more accurate to refer to *relative* response ceilings. Consider the preferred-hand response rates to monotic clicks (MP, Fig. 1). Although, when "driven" by clicks at 7/second, Ss made only about 5 responses/second, it was possible to drive responding up to about 6/second with 9/second clicks. Thus, 5 responses/second does not represent an absolute ceiling. The MP curve in Fig. 1 shows no strong signs of leveling off, which suggests that faster driving rates than 9/second might have raised responding beyond 7/second. Presumptive response ceilings are dependent on, and should be considered relative to, stimulus driving rates.

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