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Stream Segregation and the Illusion of Overlap

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When two different sounds continuously alternate at high speed, they segregate into two perceptual streams. The present article shows that this segregation produces a loss of information regarding the sequential relations of the sounds so that they seem perceptually to be overlapped in time. The segregation (and its contribution to perceived overlap) is shown to increase with the perceptual difference between the sounds. The mapping from perceptual difference to perceived overlap is not simple, however, since perceived overlap can also be affected by "perceived auditory continuity," another perceptual effect that responds differently to the perceptual difference between the two sounds.

It is commonly assumed that the perception of the temporal order of distinct auditory events is a direct mapping of the physical order up to some limit of resolution, perhaps the 15- to 20-msec onset difference mentioned by Hirsh (1959). An experimental contradiction to this idea appeared in a study by Warren, Obusek, Farmer, and Warren (1969). When listeners heard a repeating sequence of three of four unrelated sounds (e.g., buzz, tone, hiss, and vowel), listeners seemed to hear each sound clearly but could not report the order until the sounds were slowed down to almost 700 msec per tone.

Bregman and Campbell (1971) argued that these results were due to an auditory grouping effect, which they labeled "primary auditory stream segregation." They showed that with pure tones a rapid sequence containing tones from two frequency regions tended to split perceptually into two concurrent perceptual streams, one containing the high pitched tones and the other composed of the low ones. This segregation affected judgments of order: Subjects could only correctly judge the order of events in the same stream.

It would appear that primary auditory stream segregation is a mechanism evolved by the auditory system to decompose auditory inputs into those that arise from separate sources. One heuristic for decomposition might be to group sounds that resemble one another, or among which there is a continuity of change, into the same perceptual stream, especially if they follow one another closely in time (Bregman & Dannenbring, 1973). The outcome of such a decomposition, if correct, is that pattern recognition can be restricted to the set of elements arising from a single source rather than being applied to the fortuitous succession of elements from two different sources that just happen to be sounding at the same moment.

The results of Warren et al. (1969) can thus be interpreted as the result of an inappropriate application of decomposition heuristics, leading to a rejection of one or more elements of the cycle into separate streams.

There have been, however, other interpretations of the data of Warren et al. (1969). For example, Neisser (Note 1) and Warren (1974) have argued that the observed defects in performance arise not from processes of perception but from processes of verbal description. We simply cannot convert our perception into a pattern of verbal responses fast enough. When

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a subject can use a holistic recognition method on the sequence rather than being required to create a series of verbal responses, performance improves amazingly (Warren, 1974). Then why postulate perceptual decomposition as an explanation of problems of the judgments of temporal order? Why not localize the problem at the response end? Perhaps even the results of Bregman and Campbell (1971), based upon judgments of order or upon pattern identification, are really indices of a defective response process.

Issues like these can only be resolved by means of "converging operations." We should try to find new kinds of tasks involving response components or judgments that are unlike those used originally to establish the effect. If the pattern of these responses can also be explained by the original assumption of a perceptual effect, that assumption gains greater support.

In the experiments that follow, we used the judgment of perceived overlap as a new task to serve as a converging operation to establish the role of primary auditory stream segregation with materials of the type used by Warren and Obusek (1972) and by Bregman and Campbell (1971). If the sounds are judged to be more overlapped in time when variables believed to affect primary auditory stream segregation are increased in value, then there is reason to accept the idea of a perceptual decomposition process that dissociates the temporal features of events in different perceptual streams. Furthermore, if this occurs with materials of the type used by Warren et al. (1969), it strengthens the argument that their phenomenon was at least partially due to a perceptual effect.

As the present research progressed, we discovered that the use of perceived overlap as an index of primary auditory stream segregation could not be in the straightforward way that we had originally anticipated. We found that the perception of overlap responded not only to primary auditory stream segregation but to "perceived auditory continuity." This is an illusion that arises when two sounds of different loudness alternate repeatedly. The weaker one seems to continue right on through the louder one (Dannenbring, 1974; Warren, Obusek, & Ackroff, 1972). It is obvious how this illusion would influence the judgment of overlap. We were finally able to tease apart the independent contributions of primary auditory stream segregation and the "continuity illusion" on the judgment of overlap and to show, thereby, that the effects of acoustic variables on perceived overlap provide supplementary evidence that stream segregation actually destroys perceived temporal relations.

General Method

General Design

All the experiments had the same format: Two sounds repeatedly alternated on each trial and the subject made a required judgment; then another trial presented another pair of sounds alternating, and so on. However, the types of alternated sounds, their durations, and the duration of the silence between them were varied across experiments. Different types of judgments were also required in different experiments.

Subjects

Sixty-three subjects participated in this series of experiments, 13 in Experiment 1 and 10 in each of the other experiments. The subjects in the first five experiments were graduate and undergraduate students in psychology at McGill University who volunteered their services. The 10 subjects who participated in Experiment 6 were recruited from the McGill campus during a summer session and were paid for their services.

Apparatus

For Experiment 1, the noise bursts were generated by a Brüel and Kjær random noise generator (Type 1402) and recorded on a Sony TC-200 tape recorder. This noise was then filtered through a Multimetrics Model Af-520A active filter (24 dB attenuation per octave) and rerecorded to produce two types of noise: band-passed noise between 400 and 2,000 Hz and noise with the 400- to 2,000-Hz band missing. For the remaining experiments, the noise was generated by a Lafayette 40010 white noise generator, and bands of noise were made by double filtering above and below the point at which the noise burst was centered, producing 48 dB/octave decreases in amplitude above and below the center of the noise burst.

The tonal stimuli for all experiments were generated by a PDP-11 computer (Digital Equipment Corp.) operating a Wavetek Model 136 VCA-VCG tone generator through a digital-to-analog converter. These tones were mixed with the noise bursts (when they occurred successively), amplified through a Sony TA-1055 stereo amplifier, and recorded on a Revox A77 stereo tape recorder. The final tape was played binaurally to individual subjects in a small room through Sennheiser HD-414 stereo headphones. All sounds were presented at 80 dB (as measured by a General Radio Type 1551-C sound-level meter with a flat plate coupler). Background noise in the room (primarily low frequencies caused by the building air conditioning system) was approximately 56 dB.

Since one of the things being investigated was perceived temporal overlap of a repeating pattern of two nonoverlapping sounds, it was important that there be no unwanted, actual physical overlap of the two sounds. To check for possible resonance of the headphones producing a physical overlap of the sounds, the headphone output was input through a Sony F-97 dynamic microphone to a Tektronix 5103N storage oscilloscope. No resonance of the headphones could be observed on the oscilloscope.

Experiment 1

The purpose of this experiment was to establish that with alternating tones of different frequencies, variables already shown to produce stream segregation would produce an increase in perceived overlap if they caused the tones to be sorted into separate streams. Since no labeling or recognition of a pattern is required, this effect would be described as perceptual. It was also expected that the same effect would be observed in materials in which tones alterated with noise bursts; the qualitative difference between pure tone and noise or between different types of noise should produce the same sort of segregation effects as the frequency differences in pairs of pure tones; this finding would serve to relate the primary auditory stream segregation phenomenon of Bregman and Campbell (1971), observed with pure tones, to the phenomenon of Warren et al. (1969), who used different kinds of tones and noises.

Method

On each trial, the subject heard two different sounds (sine tones and/or noise bursts) that alternated for 20 sec; there was a 15-sec silence between trials. Each sound consisted of a 100-msec portion at maximum loudness, with 10-msec rise/fall times and 15 msec between sounds.

As a result of previous research, we know that sine-wave tones can be perceptually grouped into a single stream if close together in frequency but must segregate into separate streams if far apart in frequency (e.g., van Noorden, 1971, 1975). Therefore, two conditions were included whose segregation properties are known. These were essentially "anchor" conditions to allow us to see how perceived overlap relates to stream segregation. The nonsegregating pair was a 1,000-Hz sine tone (T) alternating with a 1,100-Hz tone (1,000 T/1,100 T). The segregating pair of sine tones were at 1,000 Hz and 2,600 Hz (1,000 T/2,600 T). When this latter pair alternates at the speed we used, it segregates invariably into a high stream containing repetitions of the 2,600-Hz tone and a low stream containing successive occurrences of the 1,000-Hz tone. A third pair (1,000 T/1,600 T) was included as a check for the monotonicity of the relation between frequency difference and perceived overlap.

In addition, two "noise" conditions were added. In the first, a 1,000-Hz sine tone alternated with band-passed noise (1,000 T/band-passed noise). The 1,000-Hz tone should segregate from the perceptually dissimilar band-passed noise, causing temporal confusion. In the other condition, band-passed noise alternated with band-rejected noise (band-passed noise/band-rejected noise). Since the noise bursts sound quite different qualitatively and contain different spectra, they should segregate into separate perceptual streams, again causing temporal confusion.

Subjects were asked to judge the extent to which the two different sounds in a trial seemed to overlap in time. They made this judgment by placing a mark along a 100-mm scale with the endpoints labeled "no overlap" and "complete overlap"; the distance of the mark along the scale was to indicate the perceived degree of temporal overlap. Thus, a score of 0 indicated no overlap, whereas 100 indicated complete overlap. They were not told the true degree of overlap, which was always 0.

Results

The mean rated overlap and the standard error of the mean for each of the five conditions are shown in Table 1, which also shows which pairs of means were significantly different by the Newman-Keuls method.

The two anchor conditions, one with a pair of close and the other with a pair of far apart frequencies acted as we had expected, with the estimate of overlap more than doubling in the latter condition.

TABLE 1

RESULTS OF EXPERIMENT 1

Stimulus condition	Mean overlap	SE_M	Significantly different from[a]
1. BPN/BRN	56.08	7.117	3**
2. BPN/1,000 T	68.81	7.125	3**, 4**, 5*
3. 1,000 T/1,100 T	20.42	7.716	1**, 2**, 4*, 5**
4. 1,000 T/1,600 T	40.12	10.012	2**, 3*
5. 1,000 T/2,600 T	46.77	8.928	2*, 3**

Note. BPN = band-passed noise; BRN = band-rejected noise; T = tone.
[a] Results of multiple comparisons using Newman-Keuls method.
* $p < .05$.
** $p < .01$.

The pair of frequencies with an intermediate degree of separation gave intermediate overlap judgments. The two kinds of noise separated strongly from one another and appeared to be highly overlapped. Finally, the 400- to 2,000-Hz band-passed noise seemed highly overlapped with a 1,000-Hz tone, showing a much higher illusion of overlap than the maximum shown by tone pairs.

EXPERIMENTS 2–6

Experiment 2 was designed simply as a check on Experiment 1 and to try to characterize different types of noise by their central frequencies. For tone pairs, we varied the ratio between the frequencies over a wider range. We also paired a 1,000-Hz tone with noises in a more systematic way, varying the separation of the tone frequency from the middle frequency of the filtered noise. In addition, the tone rate was varied, since this is known to affect stream segregation (van Noorden, 1975).

The results, however, showed some anomalies, yielding a pattern of results for the overlap judgments that did not obey the expectations based on what we know about stream segregation. We therefore were led to do a succession of experiments using the same pairs of sounds, varying other factors.

In Experiment 3, we changed the response measure and asked directly for stream segregation judgments. As we had suspected, these did not directly parallel those for perceived overlap, especially when noises were combined with tones. This led us to the hypothesis that "perceived auditory continuity" of the tone behind the noise was occurring. Therefore, in Experiment 4 we asked subjects to directly estimate this continuity illusion.

We know that perceived auditory continuity decreases when the silence between the two sounds is lengthened. Therefore, in Experiments 5 and 6, we simply repeated Experiments 2 and 3 with longer silences between the sounds.

When we were finished, Experiments 2, 3, 5, and 6 formed a single multifactor experiment (see Table 2) varying length of silence (break) and the response measure

TABLE 2

RESULTS OF EXPERIMENTS 2–6, SHOWING SUBJECTS' JUDGMENTS OF TEMPORAL OVERLAP, STREAM SEGREGATION, AND AUDITORY CONTINUITY FOR ALL CONDITIONS

Condition	Perceived overlap				Stream segregation				Auditory continuity	
	15-msec break (2)		50-msec break (5)		15-msec break (3)		50-msec break (6)		15-msec break (4)	
	135[a]	185[a]	135	185	135	185	135	185	135	185
Noise/noise										
1,000/1,200	31.45	31.30	38.40	36.90	3.95	5.85	2.35	1.85	7.30	7.30
1,000/3,000	59.90	30.85	56.30	21.40	12.45	10.25	11.35	5.45	5.25	4.55
Noise/tone										
1,000/1,000	71.70	70.40	51.00	54.00	11.20	9.60	9.90	7.35	8.15	7.95
1,000/1,200	75.10	60.60	52.55	37.95	11.75	11.10	9.85	7.90	8.75	6.60
1,000/3,000	56.25	41.20	56.05	38.35	11.90	11.25	11.75	9.55	2.45	3.85
Tone/tone										
1,000/1,050	21.75	15.95	22.80	14.75	3.20	2.15	3.40	2.10	7.15	6.64
1,000/1,200	45.50	10.95	35.05	10.15	7.60	3.20	6.30	2.65	5.30	5.35
1,000/3,000	39.70	43.85	45.10	45.45	10.55	10.40	10.40	9.10	4.00	4.60

Note. Numbers in parentheses refer to the number of the experiment.
[a] Onset-to-onset time (msec).

across experiments. In the Method section below, this is how they are presented. Experiment 4 corresponds to half of this design (only the shorter duration of silence), with a third response measure.

Method

Procedure. All of the procedures in these experiments were the same as in Experiment 1. The only differences were in the sounds used in the pairs and in the response measures used.

Sounds. Pure tones were produced as in Experiment 1. The noise bursts were prepared differently. They were produced by double filtering above and below the point at which the noise was centered, producing 48 dB/octave decreases in amplitude above and below the center of the noise burst. Eight types of sound pairs used in all these experiments are listed in Column 1 of Table 2.

In addition, a filtered noise (N) centered at 1,000 Hz (1,000 N) was paired with sine tones of frequencies of 1,000 Hz, 1,200 Hz, and 3,000 Hz to obtain three conditions that examined the effects of varying the relation between a tonal frequency and the center frequency of a noise burst.

Finally, two pairings of noise with noise were included, varying the distance between the center frequencies. These were 1,000 N/1,200 N and 1,000 N/3,000 N (the 1,000-centered noise was perceptually discriminable from the 1,200-centered noise, due no doubt to the sharp filtering).

Duration. We know that speed of a sequence (onset-to-onset interval) strongly affects primary auditory stream segregation with increased speed (Bregman & Dannenbring, 1973; van Noorden, 1971) causing increased stream segregation. If perceived overlap is a consequence of primary auditory stream segregation it should respond the same way. Speed was manipulated by varying the duration of the sounds to achieve onset-to-onset times of 135 msec or 185 msec. These onset-to-onset times included 10-msec rise/fall times plus a silence.

Break. Longer silences between recycling sounds reduce perceived auditory continuity (Elfner & Homick, 1967). Therefore, to tease out the contribution of perceived continuity to perceived overlap, we used two lengths of silence between sounds, 15 or 50 msec. Since onset-to-onset intervals were held constant at 135 or 185 msec, as we lengthened the silent break, we shortened the steady-state part of the sound by the same amount.

Thus, we had 16 stimulus conditions in each experiment: eight combinations of sounds with two onset-to-onset intervals. Each listener received each condition twice in two randomized blocks for a total of 32 trials.

Response measures. Three response measures were used:

1. Perceived overlap was rated on a 100-mm scale as in Experiment 1.

2. Stream segregation was measured as follows: Listeners were told that on some trials the stimuli might sound like a simple, ordinary sequence of alternating sounds; this type of situation was referred to as perceiving one stream of sounds. They were told that on other trials the sounds might seem to split into two streams; that is, there would seem to be no relationship between the two sounds, and they could really listen, or attend, to only one of the sounds at a time; this was referred to as perceiving two streams of sounds. They were asked to indicate, for each trial, whether the sounds seemed to be organized as one stream or two streams and to indicate their confidence in that decision by placing a mark on a 7-point scale with the extremes labeled "very confident" and "not at all confident." These two decisions were combined to produce a single continuous scale, with 1 being "very confident one stream" to 14, which was "very confident two streams."

3. Auditory continuity was measured as follows: Listeners were told that on some of the trials it might sound like both sounds turned on and off (i.e., discontinuity, rather than continuity, might be perceived); on other trials, it might sound like one of the sounds never quite turns off, although it might fluctuate somewhat in loudness. This situation was referred to as continuity. Subjects were asked to decide whether both stimuli sounded discontinuous or whether one of the sounds seemed to be fairly continuous. Subjects indicated their degree of confidence in this decision by placing a mark along a 7-point scale with the extremes labeled "very confident" and "not at all confident." In scoring, a 1 indicated that the listener was very confident that the sounds were discontinuous, whereas a score of 14 indicated the listener's confidence that one of the sounds was fairly continuous. (It is of interest here that van Noorden [1971, 1975] found that if subjects are specifically trying to hear stream segregation of high and low tones, they can do so more or less independently of the frequency separation, even down to very low separations. However, when trying to hear one stream only, success depends directly upon frequency separation, with higher frequency separations making the sequence split more. Our instructions have been found empirically to cause the second type of listening and yield monotonic effects of frequency separation—van Noorden's "outer fusion boundary.")

Results

Because the results are so detailed, the present section only describes the basic tables and statistical analyses. Then, for clarity of presentation, the following section asks a series of questions, answering them one at a time by selecting the relevant observations and statistical analyses across the experiments.

The results of Experiments 2–6 are shown in Table 2. This table is organized

TABLE 3

Summary of Significant Effects (p Values) Revealed by Analysis of Variance

Effect	Noise/noise: Overlap	Noise/noise: Stream segregation	Noise/tone: Overlap	Noise/tone: Stream segregation	Tone/tone: Overlap	Tone/tone: Stream segregation
Condition (Δf) (A)		.001	.01		.001	.001
Speed (B)	.005	.005	.05	.001	.001	.01
Silence (C)		.001	.05			
A × B	.001	.001			.001	.005
A × C			.05			
B × C		.005				
A × B × C						
Trials (D)		.001				
A × C × D		.05				

horizontally by dependent variable; by length of silence between sounds, which varied across experiments; and by onset-to-onset time, which varied within each experiment. The vertical organization is by type of sound pair. First we have noises alternating with noises, then noises with tones, and finally tones with tones.

The perceived overlap measure runs from 0 to 100, with higher numbers indicating more overlap. The stream segregation scale runs from 1 to 14, with higher numbers indicating more segregation. The auditory induction (perceived continuity) scale also runs from 1 to 14, with higher scores indicating more continuity of one of the sounds.

The data for Experiments 2, 3, 5, and 6 (excluding Experiment 4) were divided into six subsets, and six analyses of variance were run. To do this, we first divided the results according to the dependent measure, yielding two subsets. This division groups Experiment 2 with 5 and 3 with 6. Second, we made a threefold subdivision on the basis of type of sounds in the pairs: noise/noise, noise/tone, and tone/tone.

All six analyses contained the factors of silence duration, onset-to-onset time, and frequency separation. The statistical significance of each significant factor in each analysis is given in Table 3. Note that only "silence duration" is an across-experiment comparison.

In addition, within Experiments 2, 3, 5, and 6, multiple comparisons using the Newman-Keuls method were made between conditions of different types. Of particular interest are comparisons between stimuli of different types but the same frequency separation, speed, and silence duration (e.g., comparing 1,000 N/1,200 N with 1,000 T/1,200 T) to see whether the psychological properties of alternating noise bursts are the same as for tones of the same frequency separation. Table 4 shows the results of these tests for the six possible comparisons of this type, for each of the experiments.

Experiment 4. This experiment cannot be combined into a factorial design with any other. Its conditions and the results can be seen in Table 2. Comparisons between all possible pairs of means were performed using the Newman-Keuls method. These tests revealed that for the

TABLE 4

Statistical Significance of Multiple Comparisons (p Values) of Different Kinds of Sound Pairs with Identical Frequency Separations

Comparisons[a]	Overlap: 15-msec silence (2) Fast	Overlap: 15-msec silence (2) Slow	Overlap: 50-msec silence (5) Fast	Overlap: 50-msec silence (5) Slow	Stream segregation: 15-msec silence (3) Fast	Stream segregation: 15-msec silence (3) Slow	Stream segregation: 50-msec silence (6) Fast	Stream segregation: 50-msec silence (6) Slow
1, 4	.01	.05	.01	.01	.01	.05	.01	.01
1, 7					.05		.01	
2, 5								.05
2, 8								.05
4, 7	.05	.01	.01	.01		.01	.01	.01
5, 8								

Note. Numbers in parentheses refer to the number of the experiment.
[a] 1 = 1,000 N/1,200 N (N = noise); 2 = 1,000 N/3,000 N; 3 = 1,000 N/1,000 T (T = tone); 4 = 1,000 N/1,200 T; 5 = 1,000 N/3,000 T; 6 = 1,000 T/1,050 T; 7 = 1,000 T/1,200 T; and 8 = 1,000 T/3,000 T.

135-msec speed, the 1,000 N/3,000 T condition differed significantly from both the 1,000 N/1,000 T and 1,000 N/1,200 T conditions (at $p < .01$), and from the 1,000 N/1,200 N and 1,000 T/1,050 T conditions (at $p < .05$). In addition, 1,000 N/1,200 T stimuli differed significantly from 1,000 T/3,000 T (at $p < .05$). None of the other comparisons were significant, and none of the comparisons for the 185-msec speed were significant.

Correlations between dependent variables. Finally, since we were interested in whether perceived overlap is a consequence of stream segregation and of auditory induction, we performed a regression analysis predicting the perceived overlap from stream segregation and perceived continuity. The question was how the three measures relate under variations of stimulus conditions. Thus, the unit of analysis was the mean score on the three dependent variables that (different) subjects obtained under corresponding stimulus conditions. Since there were eight stimulus conditions (frequency separations and tone types), most of the regression analyses were based on eight observations. Thus, the results can only be taken as indicative. Separate analyses were done for the two silence lengths and the two speeds, since it seemed that the measures might correlate differently under these different conditions. A multiple regression analysis was done using the 15-msec silence conditions only, since auditory induction was measured only for this silence length. We did not measure auditory induction for the longer silence length, because we knew from the literature that there is virtually no auditory induction with longer silences (Elfner & Homick, 1967). The results are given in Table 5.

TABLE 5
REGRESSION ANALYSIS OF DEPENDENT VARIABLES

Statistic	Silence interval: 15 msec Fast	15 msec Slow	50 msec Fast	50 msec Slow
$R_{1,2}$	.85**	.69	.86**	.68
$R_{1,3}$	.19	.35	—	—
$R_{1,2\cdot3}$	.91**	.97**		
$R_{1,3\cdot2}$	.63	.95**		
Multiple R	.91**	.97**		

Note. 1 = overlap; 2 = stream segregation; 3 = continuity.
* $p < .05$.
** $p < .01$.

Prediction of stream segregation. Finally, a multiple regression analysis was done to see how well we could predict stream segregation from the acoustic difference between the two sounds in a pair. This difference could be of two types: (a) the ratio between frequencies (or center frequencies) of the two sounds and (b) whether the sounds were of the same type (tone or noise). The tone–noise variable was dichotomous, with the value 1 if the two sounds differed in type (tone vs. noise) and 0 otherwise. Again, the units of analysis were the eight types of stimulus pairs. The results are shown in Table 6.

TABLE 6
PREDICTION OF STREAM SEGREGATION FROM THE FREQUENCY SEPARATION AND THE DIFFERENCE OF SOUND TYPE IN THE PAIR OF SOUNDS

Experiment	$R_{1,2}$	$R_{1,3}$	$R_{2,3}$	$R_{1,2\cdot3}$	$R_{1,3\cdot2}$	Multiple R
15-msec silence						
Fast	.54	.61	−.08	.75	.78*	.85*
Slow	.63	.59	−.08	.84*	.83*	.90**
50-msec silence						
Fast	.67	.53	−.08	.84*	.78*	.89*
Slow	.58	.66	−.08	.85*	.87*	.92**

Note. Variable 1 = stream segregation score; Variable 2 = ratio of higher to lower frequency; Variable 3 = same versus different sound type in pair (e.g., noise/noise vs. noise/tone).
* $p < .05$.
** $p < .01$.

DISCUSSION

The previous section presents a large body of results. We can simplify these by asking one question at a time and gathering the relevant data across the experiments and analyses. The main purpose of the study was to establish perceived overlap as an index of stream segregation responding to the same stimulus variables as the latter in a parallel fashion; however, it is instructive to note the individual effects of these variables on stream segregation itself and to compare their effects with different stimulus materials. Therefore, the first four questions concern stream segregation.

Stream Segregation Effects

1. How is stream segregation of two pure tones affected by frequency separation? The results of Experiments 3 and 6 (presented in Table 2) show that the mean judgments of stream segregation for tone/tone stimuli rise monotonically in all four silence and speed conditions, yielding an overall significant main effect of frequency separation, $F(2, 36) = 40.46$, $p < .001$.

2. What effect does speed have on stream segregation of two tones? As shown in Table 2, increased speed for tone/tone stimuli significantly increased the judgments of stream segregation, $F(1, 18) = 9.46$, $p < .01$. Furthermore, the effects of speed interacted with frequency separation, $F(2, 36) = 7.43$, $p < .005$. Whereas at the faster speed (135 msec for tone plus silence) there was a smoothly increasing effect of frequency separation, at the slower speed (185 msec for tone plus silence), the effect did not really show itself with a 200-Hz separation but only with a 2,000-Hz difference. If we had looked only at the slower speed, we would have seen a "threshold" for stream segregation effects and might have concluded that the effect is probably obtained when two different auditory mechanisms compute the frequency of the two tones. The frequency of the 1,000-Hz tone might have been said to be computed by a volley mechanism and that of the 3,000-Hz tone by a place mechanism. One problem with this notion is that there is evidence for "volley" coding of frequencies up to 5,000 Hz (see Geldard, 1972).

More importantly, however, the effects of frequency difference at the higher speed are quite continuous, leading us to reject the two-mechanism explanation. We reject it also because other unpublished research in our laboratory shows that the effect of an increasing ratio of the two frequencies is continuous regardless of the frequency of the lower tone and regardless of whether the two tones are placed in the proposed volley-computed or place-computed region of the frequency spectrum.

There was no effect of the duration of the silence between tones on stream segregation judgments when onset-to-onset time was held constant. This confirms the results of Dannenbring and Bregman (1976).

3. Do stream segregation effects occur with noise/noise alternations? The results for these stimuli may be seen in Table 2. In all four conditions of speed and duration of silence, the frequency separation of the noise bands had a substantial effect on the stream segregation judgments; the overall effect was statistically reliable, $F(1, 18) = 17.21$, $p < .001$. As in the case of the tone pairs, speed also had an effect, $F(1, 18) = 15.10$, $p < .005$. Higher speeds in general led to greater segregation, except in the case of noise bursts close together in frequency and with short silence durations. In addition, as with tone pairs, speed interacted with frequency separation, $F(1, 18) = 26.87$, $p < .001$. Again, speed facilitated the effects of frequency separation, with larger frequency effects occurring at higher speeds.

There is one way in which the results for noise-burst pairs do not parallel the results for tone pairs. With tones, the length of the silent interval made no difference, but with noise bursts the effect was significant, $F(1, 18) = 22.35$, $p < .001$. Shorter silences led to greater stream segregation. Furthermore, the effects of silence length and speed were interactive, $F(1, 18) = 12.52$, $p < .005$. The effect of this was to create particularly low values of stream segregation when the longer silence was combined with the slower speed. We have to be very conservative, however, in interpreting the effects involving the silence duration, since these were obtained by comparisons across experiments and any shift in the subject population is confounded with these effects. The results do suggest, however, that there is a particular role of the silence between sounds in the case of noise bursts.

4. Do tones and noises segregate from each other? The results for the tone/noise pairs are shown in Table 2. The main

observation is that the segregation effects seen with these stimuli are the strongest that we have observed. This observation is strengthened by the multiple comparisons shown in Table 4 for stream segregation. Here we compared conditions with the same frequency separation of the pair of sounds but which differ in the similarity of the sound type (tone or noise) in the pair. For example, the 1,000 N/1,200 T pair was significantly more segregated than the 1,000 T/1,200 T condition and also more segregated than the 1,000 N/1,200 N condition. In both cases, this superiority was found for all combinations of speed and silence length.

However, the increased segregation with the pairing of noise and tone is not found in the 1,000/3,000-Hz combinations. This is not surprising because all these conditions are highly segregated.

A final source of evidence regarding the roles of frequency separation and noise–tone pairing in causing stream segregation comes from the multiple regression analysis whose results are shown in Table 6. Stream segregation in the eight types of sound pairs was predicted from two factors: (a) the ratio between the two frequencies (or center frequencies) involved and (b) whether the sounds were of the same type (tone or noise). Each variable taken alone predicted stream segregation moderately well, with the simple correlations ranging from .53 to .67 under the four conditions of silence length and speed. However, the partial correlations (ranging from .75 to .87) are always much higher than the simple correlations, and the multiple correlation is always above .85. This pattern is obtained whenever two predictor variables both have high and independent predictive value. For each predictor, the simple correlation with the dependent variable is lowered by the unaccounted-for variance due to the third variable. The partial correlation coefficient shows what each variable can predict after the other variable has had its say.

The three ways of examining the results lead us to conclude that noises tend to segregate from tones and that this effect is independent of the effect of (center) frequency separation.

Perceived continuity. To see how judgments of perceived overlap are affected by perceived continuity, it is important to first see how the latter is affected by the variables of our experiment. We therefore ask a fifth question:

5. What variables influence perceived continuity? Table 2 shows the results of Experiment 4 on the induction of auditory continuity. The strongest induction effects were seen in the noise/tone conditions when the tone was at or near the center frequency of the noise. When the tone lay outside the spectrum of the noise band, the induction effect was much reduced. These results replicate the results of Warren et al. (1972). All other induction effects with noise/noise and tone/tone pairs were moderate in size.

In addition, there is one other regularity in the results. Both in the noise/noise and tone/tone conditions, induction gets worse as the frequency separation increases. We did not test this combined trend statistically, but it happens for both speeds in about the same degree. However, there is a problem in simply asserting that with alternating sounds of the same type, if they are near in frequency, one tone seems to continue behind the other. When the experimenters listened to the 1,000 T/1,050 T condition and to the 1,000 N/1,200 N condition, a different experience emerged. The two sounds seemed to alternate with a gliding pitch transition and not discretely. When subjects rated "continuity," they probably confused this continuity of one sound *into* the other, with the continuity of one sound *behind* the other. This confusion would have elevated the 1,000 T/1,050 T and the 1,000 N/1,200 N conditions. The percept of gliding transition for small frequency jumps probably depended on the fact that with the 10-msec rise/fall times that we used there were no onset or offset transients to signal an abrupt change to the ear.

Perceived overlap. Finally we arrive at the data bearing on the basic issue of whether perceived overlap can be used as a converging operation to establish that stream segregation is a perceptual effect. The way we will address this issue is by breaking it down into two sets of questions concerning whether perceived overlap responds to the various experimental manipulations similarly to stream segregation and perceived continuity. Then we show that the latter two variables in combination can predict the overlap results. Let us begin with the questions about experimental manipulations.

6. Is perceived overlap affected by frequency separation? The results turn out to be very irregular. As we shall show later, this is because perceived overlap is actually influenced by both stream segregation and perceived continuity, and these phenomena respond differently to the amount of frequency separation. The results related to this question are given in Tables 1 and 2. Table 1 shows the results of Experiment 1. For pairs of pure tones, perceived overlap increased steadily with frequency separation from about 20% to 47%, the difference between the lowest separation and the higher separations being statistically reliable.

In Table 2 the results for tones are similar. As frequency separation increased, so did perceived overlap, $F(2, 36) = 8.73$, $p < .001$. This effect, however, interacted with speed, $F(2, 36) = 19.59$, $p < .001$, so that the middle degree of frequency separation affected perceived overlap at the high speed only. There was also a significant main effect of speed, $F(1, 18) = 17.85$, $p < .001$.

Spectrum differences were also important in Experiment 1, with the band-passed noise/band-rejected noise pairing producing a considerable amount of perceived overlap.

The effect of frequency on perceived overlap, shown in Table 2, however, depends upon the type of sounds in the pair. With noise/noise pairs, there is a strong interaction between speed and frequency, $F(1, 18) = 15.53$, $p < .001$. Only with the high speed does an increase in frequency separation cause an increase in overlap. With the low speed, there is even the hint of a reversed effect (which, if compared to the auditory continuity results on the right of Table 2, can be seen to resemble these results rather than the stream segregation pattern). Speed by itself also increased perceived overlap, $F(1, 18) = 13.66$, $p < .005$.

With the noise/tone pairs, there was also a significant effect of speed, $F(1, 18) = 7.00$, $p < .05$. This was in the usual direction, with speed increasing the illusion of overlap. However, the rest of the effects were quite different from those for tone/tone pairs and noise/noise pairs. Apparently, alternating tones and noises yielded some special effects. The first one was an effect of the silence duration, with shorter silences yielding higher perceived overlap, $F(1, 18) = 6.15$, $p < .05$. The second was a frequency separation effect that went in the opposite direction from the one for tone/tone and noise/noise pairs, $F(2, 36) = 5.54$, $p < .01$. The third was an interaction of frequency separation and silence duration, $F(2, 36) = 3.56$, $p < .05$. The reversed effect of frequency separation occurred only with short silences.

The paradoxical effects can be resolved as follows: The overlap judgments with the noise/tone pairings are affected quite strongly by perceived continuity (auditory induction). This is shown by the extremely high judgments of continuity with 15-msec silences. Even if subjects could not tell the temporal order of the sounds and were making random overlap judgments, their means should only be 50% overlap. Higher than chance overlap judgments suggest that subjects were actually hearing one sound continue behind the other. This is confirmed by the results on judged continuity shown in Table 2. These continuity effects generally paralleled the overlap judgments with noise/tone stimuli (except that speed made no difference). When the silence is longer, the induction of auditory continuity is known to disappear (Elfner & Homick, 1967), and with the noise/tone pairs, judged overlap dropped substantially. We should not be surprised at the strong intrusion of induced continuity effects with noise/tone conditions; it is with these stimuli that the induction of continuity is strongest (see Table 2). The increase of perceived overlap with noise/tone pairings showed up in the statistical analyses shown in Table 4. Perceived overlap for 1,000 N/1,200 T was greater than for the same frequency separation when *only* tones or *only* noises were paired. Finally, it is known from the literature (Warren et al., 1972) that as frequency separation increases between two sounds, induced continuity decreases; we see this effect for judged continuity with all sound pairs in Table 2 (Experiment 4). We also see it with perceived overlap for the noise/tone pairs with short silences.

To summarize, the perceived overlap results seem to resemble stream segregation results for the conditions in which the induction of continuity is less likely to occur.

7. Can overlap be predicted from stream segregation and continuity? We wished to quantify our observation that perceived overlap was a consequence of both stream segregation and induced continuity effects. We therefore did multiple regression analyses predicting perceived overlap from the other two variables. The dependent variables were the means of all subjects on each measure for each of the eight types of sound pairs. Separate analyses were done for fast and slow conditions. The results, shown in Table 5, are clear. When variables are taken separately, stream segregation predicts overlap quite well, particularly at high speeds. Perceived continuity predicts less well. However, the partial correlations are all substantially higher and all above .90, except for the continuity predictor at high speeds (where stream segregation seems to take over). The multiple correlations are very high, leaving only 6% of the treatment (type of pair) variance unaccounted for at the slow speed (17% at the high speed). This pattern of results is found when two factors have independent value in predicting a third one. We can consider, then, that describing perceived overlap as a mixed effect of stream segregation and auditory continuity provides an economical description of the data.

Conclusions

1. Stream segregation increases with increased frequency separation both for pure tone pairs and for noise pairs. This confirms the observations of van Noorden (1975).

2. With noise/tone pairs the difference between tone and noise causes streams to segregate. An additional, smaller, contribution to segregation is made by the separation between frequency spectra.

3. Speed always increases stream segregation and facilitates the effects of frequency separation on segregation in cases in which frequency separation does not completely segregate the streams. This is again consistent with van Noorden's (1975) observations and those of Bregman and Dannenbring (1973).

4. Induced continuity is reduced by separations in frequency; it is highest for tone/noise pairs. Speed has no effect on perceived continuity.

5. Perceived overlap is predictable from stream segregation and from induced continuity. The stream segregation factor has the strongest effect at higher speeds and with long silences. With short silences, slow speeds, and especially noise/tone pairs, the induction of continuity has almost as strong an effect on perceived overlap.

If the perceptual status of stream segregation is to be established by converging operations, it is worth counting the response measures that respond to the same independent variables in the same way. Let us choose the independent variables of speed and frequency separation that are both thought to enhance stream segregation. (a) Direct judgments of stream segregation in the present experiments respond to both of these variables. Bregman and Dannenbring (1973) also showed these judgments to respond to speed. (b) Direct judgments of order were shown by Bregman and Campbell (1971) to respond to frequency separation. (c) Same–different judgments of order respond to frequency separation (Bregman & Campbell, 1971) and speed (Bregman & Dannenbring, 1973) and also show "capturing effects" in which one stream captures elements from a second (Bregman & Rudnicky, 1975). (d) Finally, perceived overlap (when auditory continuity is partialed out) responds to these factors as well. This is observed most clearly with pure tone pairs with 50-msec breaks (Experiment 5), conditions in which auditory continuity would have the least effect.

Converging operations can cross sensory modalities as well. The loss of temporal succession in two alternating event sequences has been noted before with apparent motion. When the speed of alternation of two flashing lamps becomes too high or when their separation in space becomes too large, apparent motion between them ceases, and the flashing of the lamps seems unrelated in time. The perception of succession is destroyed, and the flashes can even seem overlapped or synchronous. Bregman and Achim (1973) have suggested that this is an example of stream segregation, spatial separation being the visual analogue of frequency separation in audition, and have shown the splitting of visual streams into substreams.

Stream segregation is thus seen as a factor that mediates between certain stimulus variables and certain judgments. It factors a sequence of events into concurrent streams and allows rapid processes of pattern recognition to operate only within a stream. Because it operates even with nontonal stimuli, many problems with the judgment of order (e.g., those of Warren et al., 1969, 1972) can arise from inappropriate application of stream segregation heuristics by the auditory system.

REFERENCE NOTE

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