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Perceptual attenuation of nonfocused auditory streams

MARIE-CLAIRE BOTTE, CAROLYN DRAKE, and RENAUD BROCHARD
Laboratoire de Psychologie Expérimentale, CNRS, Université René Descartes, Paris, France

and

STEPHEN McADAMS
Laboratoire de Psychologie Expérimentale and IRCAM, Paris, France

The aim of this study was to measure the perceptual attenuation, measured in decibels, resulting from the focusing of attention on one stream within a multistream auditory sequence. The intensity of a nonfocused stream was increased until the accuracy of detecting a temporal irregularity in this stream was the same as in a focused stream. Eight subjects were required to detect a temporal irregularity created by delaying or advancing one tone which could be situated in one of three temporally regular streams played simultaneously to create a multistream sequence. The three streams differed in tempo and frequency. Subjects' attention was focused on one of the streams by preceding the multistream sequence with one of the single streams (a cue). We first established the size of temporal irregularity detected at a 90% level in cued streams, confirming that subjects were able to focus on one particular stream. Second, an irregularity of this size was not detected above chance level in noncued streams, demonstrating that listeners focus only on the cued stream. Third, for 5 subjects, a 15-dB increase in the level of one of the noncued streams was necessary to bring detection up to that found in the cued streams. This gain provides an equivalent measure of the perceptual attenuation of nonfocused streams. For 3 other subjects, detection in the noncued stream remained at chance performance whatever the level. For all subjects, detection in the cued stream decreased slightly as the level of the noncued stream increased. We conclude that the attenuation of nonfocused auditory streams can attain as much as 15 dB, at least for some subjects.

The auditory system does not passively analyze information as would a machine, decoding every event in the same way irrespective of its importance. Rather, information about events is organized at an early stage in auditory processing, depending on the events' similarity to other sounds, their spatial location, and temporal structure. If several sound events occur over the same time span, then information about frequency, amplitude, and duration of these events is mixed together. A major question in auditory perception research today is how the system is able to segregate information from this mixture to recover the original events. One organizing principle is that of the creation of auditory streams in which sound events with similar physical characteristics (frequency, temporal regularity, tempo, spatial orientation, intensity, timbre, changes in spectral envelope, etc.) are presumed to originate from the same source (Bregman, 1990; McAdams, 1984). Thus, similar events are spontaneously grouped into a single unit or stream. Events within a stream can then be coded in relation to each other, but not in relation to events in other streams.

One confirmation that stream segregation is a perceptually relevant organizing principle comes from the fact that attention can allow a listener to focus on one stream when it is embedded within other streams. In Dowling's classic example of two interleaved nursery rhymes (Dowling, Lung, & Herrbold, 1987), listeners were able to focus on one or the other of the tunes, but not on both at the same time. It is as if attention highlights the attended stream or, inversely, dampens the unattended one. This phenomenon could be described either as an amplification of the attended stream or an attenuation of the unattended one. Thus, the effect of attention is equivalent to a difference in loudness of the two streams.

The few existing studies of attention to single tones have shown that attention may be focused on limited zones of frequency (Greenberg & Larkin, 1968), intensity (Luce, Green, & Weber, 1976), tone duration (Wright & Dai, 1993), and temporal position (Leis-Rossio, 1986). These limited zones have been called "attentional bands." In a decision task, when attention is focused on one of these zones, one does not observe an increase in sensitivity to change (in frequency, intensity, or duration) within this zone, but rather a decrease in sensitivity in neighbor-

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ing zones. This effective attenuation was measured in frequency attentional bands (Dai, Scharf, & Buus, 1991). Listeners were required to detect a single tone which was almost totally masked by noise. Tones situated outside the focused band were perceptually attenuated by about 7 dB. Like other authors (Scharf, Possamaï, & Bonnel, 1989; Schlauch & Hafter, 1991), Dai et al. (1991) demonstrated that this type of attentional process operates as a selective filter, letting through a central frequency without attenuation and progressively increasing attenuation away from this central frequency.

However, when we listen, we perceive streams of sounds, not isolated tones. Previous measures of perceptual attenuation therefore may not apply to everyday listening. We therefore decided to measure a similar effect of perceptual attenuation in streams of events rather than in single tones. The aim of this study was twofold. First, we wished to investigate to what extent listeners were able to process temporal information in nonfocused streams when they focused on one stream within a multistream context. We did this by measuring the detectability of temporal irregularities in both focused and nonfocused streams. Second, we wished to measure the perceptual attenuation of nonfocused streams relative to focused streams. This was done by increasing the intensity of nonfocused streams until subjects' ability to detect a temporal variation was the same as in a focused stream. This increase (measured in decibels) was taken as a measure of perceptual attenuation of nonfocused streams.

Three experiments designed to measure this attenuation were inspired by the probe/signal paradigm for measuring the detection of attended and unattended signals (Greenberg & Larkin, 1968). We measured the ability of listeners to detect a small temporal irregularity embedded within one stream of a multistream sequence composed of three isochronous pure-tone streams, each with a different tempo and frequency (see Figure 1). Tempo is defined here as the duration between the onsets of successive tones. If only the multistream sequences are presented, listeners are unable to detect a temporal irregularity because they adopt a global listening strategy that integrates all events into a single perceptual structure rather than segregating the sequence into frequency-based streams. Stream segregation is encouraged (facilitated) by preceding the multistream sequences by a cue that has the same tempo and frequency as one of the streams in the multistream sequence. Our multistream sequences were therefore composed of two types of streams—those whose frequency and tempo matches the preceding cue (cued stream) and those with a different frequency and tempo (noncued stream).

The first experiment, a control condition, provided a measure of listeners' sensitivity to these temporal irregularities in cued streams and was expected to establish that sensitivity was similar in the three chosen streams. The second experiment tested whether listeners could detect a temporal irregularity in a noncued stream. Their inability to do so would confirm that they were using a selective attending strategy and suggest that they could not divide their attention effectively between several streams. The third experiment examined whether sensitivity to temporal irregularities in a noncued stream could be improved by increases in level of this stream, a way of measuring the perceptual attenuation of noncued streams.

EXPERIMENT 1
Sensitivity to Temporal Irregularities

This experiment was designed to measure listeners' sensitivity to a temporal irregularity in otherwise regular sequences when subjects focused on one stream within a sequence containing three concomitant streams. Listeners were induced to focus on one stream by the presence of a cue of the same frequency and tempo preceding the multistream sequence. It was important for the argument of the following experiments to establish the temporal irregularities needed to produce equal detection in each of the three streams when they were individually cued.

Two procedures were used. Procedure 1 was the measurement of JND with an adaptive staircase method, which provides a precise indication of the level of sensitivity to temporal irregularities. However, it is a very time-consuming procedure that makes comparisons between different conditions arduous. Procedure 2 was a less time-consuming, modified method of limits, in which the value of temporal irregularity was systematically varied in order to establish the degree of irregularity correctly detected

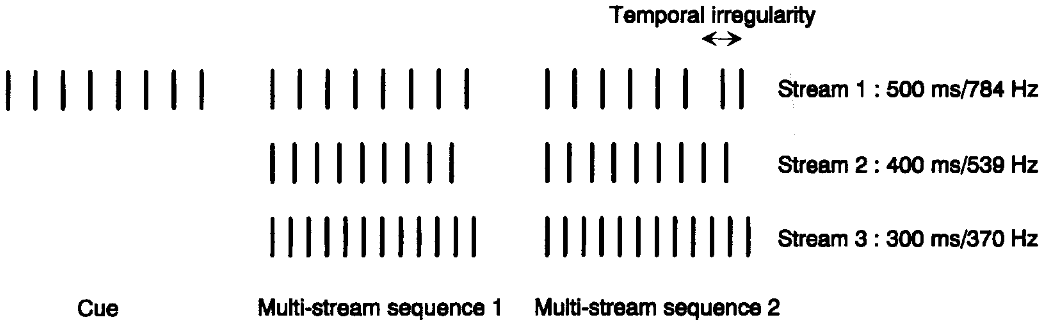

Figure 1. Stimuli for one trial in Experiments 1, 2, and 3. Each bar represents one 50-msec, 70-dB tone. One example of temporal irregularity is given (arrow).

on 90% of the trials. We hypothesized that the two procedures would result in similar patterns of results. These two measures were obtained for each of the three cued streams.

Method

Subjects. All 8 subjects had normal hearing. They were all undergraduate psychology students at the University René Descartes who had not previously participated in psychoacoustic experiments.

Materials. Sequences were composed of three streams of pure tones that were uniquely defined by tempo and frequency.[1] A preliminary experiment (run before the experiments reported here and under the same conditions) examined the detectability of temporal irregularities in all nine tempo/frequency combinations. We thus established three tempo/frequency combinations resulting in similar sensitivity to temporal irregularities (JND of about 10%): Stream 1 = 500 msec/784 Hz, Stream 2 = 400 msec/539 Hz, Stream 3 = 300 msec/370 Hz. The frequency separations between adjacent streams were chosen in such a way as to allow stream segregation according to van Noorden's (1975) data established for two streams. The tempi were all in a middle tempo range and were chosen to avoid too many co-occurring tones. A temporal irregularity was created by advancing or delaying the onset of one of the tones in relation to regularity (see Figure 1). The temporal irregularity could occur in one of two positions in each stream, near either the beginning or the end of the sequence (Stream 1 =Tones 3 or 6, Stream 2 =Tones 3 or 7, Stream 3 = Tones 4 or 8). The tones lasted 50 msec (including 10 msec onset and offset ramps) and were presented to both ears at 70 dB SPL. Stream 1 contained 7 tones, Stream 2 contained 8 tones, and Stream 3 contained 11 tones. Thus, each sequence lasted 3.5 sec.

Apparatus. The sequences were generated by a synthesizer (OROS) and controlled by a personal computer. Subjects sat in a soundproof room and listened to sequences through headphones (TDH 49). A programmable attenuator (CHARYBDIS D) controlled sound levels. The subjects gave their responses by pressing one of two buttons.

General Procedure. The subjects heard a cue followed by two multistream sequences, which were identical except that one contained a temporal irregularity in the cued stream. Their task was to detect this temporal irregularity and indicate which of the two multistream sequences contained it by pressing a button. They received visual feedback indicating the correctness of their responses. The same cue was presented within a block of trials and varied from one block to the next.

Procedure 1. JNDs were measured for temporal irregularities using an adaptative 4 down/1 up procedure (Levitt, 1971). The detection threshold was the degree of temporal irregularity (expressed as a percentage of the target tempo) correctly detected 84.1% of the time. Each trial began with a 5% temporal irregularity. Four successive correct answers resulted in a decrease of 1%, one incorrect answer led to an increase of 1%. Detection thesholds were calculated on the last 10 (out of 12) reversals. Each measure was repeated four times for each subject for each of the three streams, in a counterbalanced order. Analyses were performed on the two lowest thresholds, and the mean of these two measures was used as the starting point for Procedure 2.

Procedure 2. The subjects responded to a succession of blocks composed of 20 trials. Starting with the value of temporal irregularity obtained for each subject with Procedure 1, the size of temporal irregularity within a block was increased by steps of 1% until subjects performed at a minimum success rate of 90% for two successive blocks (40 trials).

Results

Table 1 presents JNDs for detecting temporal irregularities in the three cued streams at 84.1% correct detections (Procedure 1). All were around 10.5% of the target tempo, as expected from the preliminary experiment (range = 9.7%–13.5%). A repeated measures analysis of variance (ANOVA) of the observed JNDs for the three streams and two repetitions revealed no significant effects for either factor.

Table 1 also shows the size of temporal irregularity (measured as a percentage of stream tempo) needed to obtain 90% correct detections for two successive blocks of 20 trials (Procedure 2). A mean irregularity of about 12% was required for all three streams: a one-way ANOVA of irregularity size revealed no significant differences between the three streams. As expected, these values were higher than those obtained for the JNDs at 84.1% but show the same pattern of results. This more economical method was therefore adopted in the following experiments.

Discussion

This experiment provided evidence that listeners were able to focus their attention on one stream within a multistream sequence when it was preceded by a cue. It confirmed the findings of the preliminary experiment, showing that it is equally easy to detect a temporal irregularity in the three cued streams in the three tempo/frequency combinations adopted here. It would therefore be possible to compare JNDs for the three streams in later experiments in which the stream might or might not be cued. The JNDs obtained here for a temporal irregularity are in a similar range to those that have been found previously under slightly different conditions (Halpern & Darwin, 1982; Hirsh, Monahan, Grant, & Singh, 1990; Monahan & Hirsh, 1990).

EXPERIMENT 2
Selective Attention, Divided Attention, or Global Listening Strategies?

In Experiment 1, the irregularity to be detected always occurred in the cued stream. What would happen when the irregularity could occur in a noncued stream (nonfocused) stream? The main aim of our second experiment was to determine whether listeners do indeed perceptually organize the multistream sequence into separate streams and detect temporal irregularities by focusing on a single stream (selective attending strategy; Treisman, 1969). Two alternative strategies seemed possible: Listeners might be able to divide their attention between two or more streams, meaning that they would be able to de-

Table 1
Experiment 1: Mean Size and Standard Error of the Temporal Irregularity (in Percentage of the Stream Tempo) Resulting in 84.1% or 90% Correct Detections for the Three Cued Streams

	Stream 1		Stream 2		Stream 3	
Procedure	*M*	*SE*	*M*	*SE*	*M*	*SE*
1 (84%)	10.1	0.9	11.6	1.0	9.7	0.5
2 (90%)	11.4	0.6	13.5	1.2	11.1	1.0

Note—Stream 1 = 500 msec/784 Hz; Stream 2 = 400 msec/539 Hz; Stream 3 = 300 msec/370 Hz.

tect irregularities in more than one concomitant stream (divided attention), or listeners might detect an irregularity in relation to the rhythmic pattern of the sequence as a whole and not only in relation to distinct streams (global listening). A selective attending strategy would lead to successful detection of irregularities in the cued stream but not in the noncued stream, a divided attending strategy would result in higher than chance detection of irregularities in the noncued streams, and a global listening strategy would result in equal detection in cued and noncued streams. We investigated these alternatives by comparing the percentage of correct irregularity detection when the irregularity always occurred in the cued stream (as in Experiment 1) with that obtained when the irregularity could occur in either the cued or a noncued stream.

Method

Subjects. The subjects were same 8 who had participated in Experiment 1.

Materials. The sequences were identical to those in Experiment 1, except that the temporal irregularity could occur in either the cued or noncued streams.

Procedure. The subjects were asked to detect a fixed-size temporal irregularity (12%, the value resulting in 90% correct detections in Experiment 1). Ten blocks of 20 trials were presented. In each block, the irregularity appeared 14 times in the cued stream (Stream 1) and 6 times in one of the noncued streams (in Stream 2 for five blocks and in Stream 3 for the other five blocks). Mean percentage correct was therefore calculated from 140 observations for the cued stream and 30 observations for each of the noncued streams. The subjects were told to respond to any temporal irregularities in the multistream sequences but were not told explicity that the irregularity could occur in noncued streams. They were required to maintain at least a 90% success rate and to respond randomly if they were unsure of a response.

Results

The mean percentage of correct irregularity detection for the cued stream (Stream 1) was 90.3% (as intended by the design). Detection was much lower for the two noncued streams (Stream 2 = 59.2%, and Stream 3 = 52.5%). A one-way ANOVA of the percentage of correct irregularity detection for the three streams[2] revealed a significant main effect of stream [$F(2,14) = 58.6, p < .001$]. Planned comparisons confirmed that detection was significantly higher for the cued streams than for the two noncued streams [$F(1,7) = 122.6, p < .001$] and that detection did not differ significantly between the two noncued streams (Streams 2 and 3). Of particular importance is the fact that single-sample t tests ($p < .01$) revealed that irregularities in the noncued streams were not detected above the chance level of 50%, and that detection in the cued stream did not differ significantly from the intended 90% level.

Discussion

This experiment demonstrates that subjects detected temporal irregularities in the cued stream but not in either noncued stream. The results suggest that listeners were indeed perceptually organizing the sequences into streams, focusing on one stream, and detecting a temporal irregularity in relation to the regularity of that stream. Rather than using a divided attending or a global listening strategy, they adopted a selective attending strategy.

EXPERIMENT 3
Measure of Perceptual Attenuation

In Experiment 2, we observed that listeners were unable to detect temporal irregularities in noncued streams. Here we gradually increased the level of one of the noncued streams (by 0–18 dB) to test whether or not this increase could compensate for the perceptual attenuation of the stream. If this is the case, an increase in level should improve the detection of irregularity in the noncued stream. The intensity level was gradually increased in order to provide an estimation in decibels of the perceptual attenuation of nonfocused streams due to the focusing of attention on one stream. We also tested whether performance in the cued stream decreased when the level of the noncued stream was increased. Such a pattern might indicate a "capturing of attention" by the noncued stream.

Method

Subjects. The same eight subjects participated in this experiment.

Materials. The sequences were identical to those in Experiments 1 and 2. The cued stream was always Stream 1 and the variable intensity noncued stream was Stream 3 (see Figure 1). This combination was chosen because the two streams were as different as possible. As in Experiment 2, the irregularity appeared 14 times in the cued stream and 6 times in the noncued stream in each block. The cued Stream 1 and noncued Stream 2 had a level of 70 dB SPL as in Experiments 1 and 2, but the level of the noncued Stream 3 was 0, 6, 12, 15, or 18 dB higher, presented in a counterbalanced order.

Procedure. The subjects had to detect a fixed-size temporal irregularity (12%—that found in Experiment 1 to give 90% correct responses) in five blocks of 20 trials for each level.

Results

Figure 2a shows the percentage of correct detections averaged over the 8 subjects for the cued Stream 1 and the noncued Stream 3 as the intensity level of the noncued Stream 3 was increased from 70 to 88 dB. Detections in the cued stream were only slightly affected by an increase in level of the noncued stream, whereas detections improved in the noncued stream as its level increased. A repeated measures ANOVA was performed on the percentage of correct detections with factors of level increase of the noncued stream (5), stream (cued and noncued), and repetition (5). A main effect of stream [$F(1,7) = 44.0, p < .001$] and a significant interaction between stream and level increase [$F(4,28) = 9.2, p < .001$] were found, indicating that the effect of increase in level was different on detection in the cued and noncued streams. However, inspection of individual data revealed two groups of subjects with distinct detection patterns. Results for the two groups are shown in Figures 2b and 2c.

The 5 subjects in Group 1 showed a more pronounced version of the pattern described above. A similar ANOVA carried out on Group 1 revealed a main effect of stream

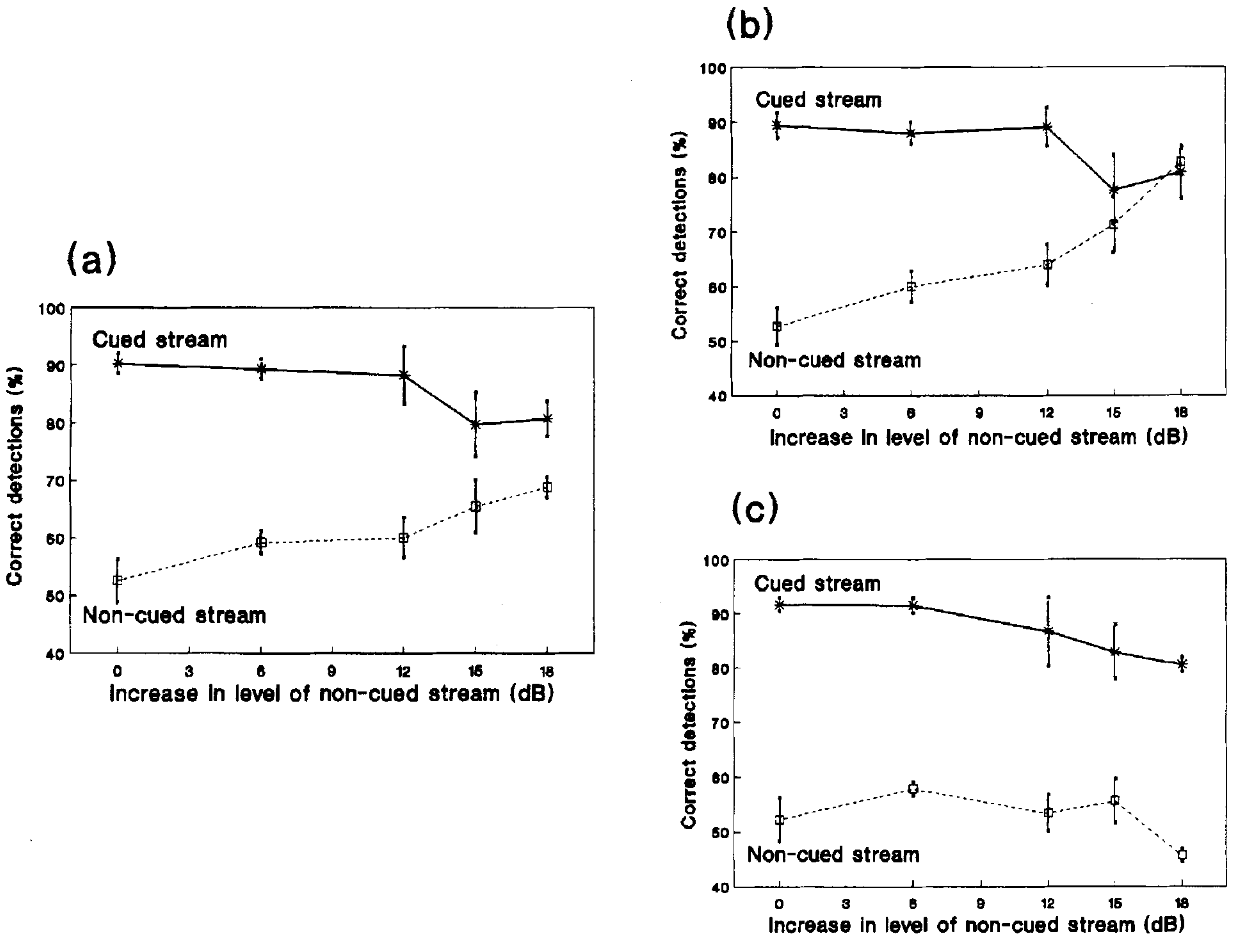

Figure 2. Experiment 3: Percentage of correct detections of temporal irregularity in the cued (Stream 1) and noncued streams (Stream 3) as a function of the level of the noncued stream. Mean results are shown for (a) all 8 subjects, (b) 5 subjects in Group 1, and (c) 3 subjects in Group 2. Vertical bars represent ±1 standard error.

[$F(1,4) = 23.1, p < .01$], a main effect of level increase [$F(4,16) = 4.2, p < .02$], and a significant interaction between stream and level increase [$F(4,16) = 17.8, p < .001$], indicating that the increase in level had a different effect on detection in the cued and noncued streams. When the noncued stream was taken separately, t tests indicated that although values obtained with increases of 0, 6, and 12 dB did not differ from chance (50%), those obtained with increases of 15 and 18 dB did [for 15 dB, $t(4) = 4.2, p < .01$; for 18 dB, $t(4) = 13.3, p < .001$]. Also, these last two values did not differ from the 90% expected success rate. Indeed, no significant differences were seen between the values obtained with 15- and 18-dB increases for the cued and noncued sequences. When the cued stream was taken separately, planned comparisons indicated that level increases of 15 and 18 dB led to significantly lower detection performance than did the other levels [$F(1,4) = 163.9, p < .001$]. Thus, small increases in the level of the noncued stream did not diminish performance in the cued stream, whereas larger increases of 15 and 18 dB led to slightly poorer detection of temporal irregularities in the cued stream.

The 3 subjects in Group 2 did not show this pattern. A similar ANOVA carried out on Group 2 revealed a main effect of stream [$F(1,2) = 215.7, p < .01$] and a main effect of level increase [$F(2,8) = 6.4, p < .02$]. The interaction between stream and level increase was, however, not significant [$F(2,8) = 1.2, p = .39$], suggesting that both streams were unaffected by an increase in level of the noncued stream. t tests indicated that all observed values for the *cued stream* did not differ from the 90% expected success rate, and all observed values for the *noncued stream* did not differ from chance level and remained significantly lower than the 90% expected success rate. Thus, while an increase in level of the noncued stream led to improved performance in this stream for Group 1 subjects, no corresponding improvement was observed for Group 2 subjects.

Discussion

The results of this experiment suggest that subjects did not all adopt the same strategy in this complex listening task. The 3 subjects of Group 2 were able to pursue the selective attending strategy adopted in Experiment 2, focusing on the cued stream without detecting temporal irregularities in other streams. The level of the noncued stream could be increased by at least 18 dB without having attention drawn to this stream. Although irregularities were never detected in the noncued stream, performance in the cued stream deteriorated slightly with increased level. The 5 subjects of Group 1 were, to a certain extent, able to divide attention between a cued and noncued stream if the noncued stream was made salient enough. Salience was enhanced in the present conditions by increasing the level of the noncued stream by at least 15 dB. This capturing of attention by another stream resulted in a corresponding decrease in detection in the primary focused stream.

These results suggest that attentional focusing on a specific stream results in a "perceptual attenuation" of concomitant streams, which, in our experimental conditions, attains a level of about 15 dB.

GENERAL DISCUSSION

A Measure of Perceptual Attenuation of Nonfocused Streams

The main aim of these experiments was to provide a first measure of the attenuation of nonfocused streams in a multistream context. For 5 out of 8 subjects, an increase of at least 15 dB in the level of a nonfocused stream was necessary to compensate for this perceptual attenuation. We can therefore consider that, in these experimental conditions, the equivalent attenuation of lower frequency nonfocused streams caused by focusing on another higher frequency stream is about 15 dB. Additional experiments are necessary in order to examine why no such pattern was observed for the other 3 subjects. A likely hypothesis is that these subjects were more strongly influenced by the cue sequence that led them to focus exclusively on the cued stream, effectively "cutting out" interference from competing streams, evidence perhaps for a stronger attenuation in these subjects.

The attenuation of nonfocused auditory streams (15 dB) is much greater than that measured previously for partially masked tones presented at nonfocused frequencies (7 dB, Dai et al., 1991). In natural listening conditions, focusing—and the corresponding attenuation—surely occurs more frequently on auditory streams than on almost totally masked single tones. Another difference between this experiment and those previously carried out on single tones resides in the nature of the task required of the listeners. This task emphasizes the temporal rather than the spectral aspects of the stimuli, and this difference may influence the level of attenuation.

Selective Attention, Divided Attention, and Global Listening Strategies

Our results address two issues related to how listeners perceive relatively complex auditory sequences. The first issue concerns the conditions under which listeners are able to attend selectively to one stream in a multistream context. Our stimuli were designed so that three separate streams should be perceived (according to data provided by van Noorden, 1975, and Jones, 1976, concerning the segregation of two streams). However, pilot studies indicated that, without a cue, subjects were unable to selectively attend to one stream in these multistream contexts. They could accomplish the task only by adopting a global listening strategy—that is, by detecting temporal irregularities in relation to the sequence as a whole. This led to very poor detection performance. Thus, it would appear that wider tempo and frequency differences are necessary for successful stream segregation, either with or without a cue, in more complex sequences, a question currently under investigation (Brochard, Drake, Botte, & McAdams, 1995). In the present experiments, difficulty in focusing on one stream was overcome by preceding the multistream sequences with a cue of the same tempo/frequency combination. The results are consistent with the previous findings that while it is easier to detect a tone of an expected frequency, it is also easier to detect changes in tone characteristics at an expected frequency (Mondor & Bregman, 1994). We have generalized these findings by showing that focusing attention on a stream by cuing a particular tempo/frequency combination leads to an enhanced ability to focus not only on the stream itself, but also on the temporal characteristics of events within the stream. We are currently examining the relative roles of tempo and frequency in this facilitation.

The second issue concerns listeners' abilities to process concurrent streams when their attention is focused on one stream. We have demonstrated that, under our experimental conditions, when all the streams are at the same intensity level, listeners are unable to detect temporal irregularities above chance in the nonfocused streams. They are therefore adopting a selective attending strategy, processing the focused stream and excluding nonfocused ones. They do not adopt either of two other strategies, that of dividing their attention between more than one stream or that of listening for a temporal irregularity in the multistream sequence as a whole. While we hesitate to infer from this result that other streams are not processed at all, in informal discussions, subjects were frequently unable to say whether other streams were higher or lower, or faster or slower, than the focused stream.

When the intensity level of the lowest frequency noncued stream was considerably increased, most listeners were able to detect temporal irregularities in both this stream and the highest frequency noncued streams. They thus seem to have adopted a divided attending strategy. In this case, it appears that the cue sequence leads to attentional focusing on the cued stream, whereas the increased intensity level draws attention to the noncued stream. We have provided a first illustration of how these two principles can compete for dominance: a level increase of at least 15 dB appears to be necessary to override the influence of the cue. A minority of listeners maintain a selective attending strategy even when presented with the competing-level cue. It remains to be seen whether cuing lower frequency streams gives similar results, but work in progress (Brochard et al., 1995) suggests this to be the case.

Interestingly, all listeners show a decrease in performance for the cued stream as the level of the noncued stream is increased. This decrease may reflect the transfer of resources away from analyzing the physical characteristics of the focused stream toward maintaining selective attentional focusing. Indeed, subjects reported having greater difficulty concentrating on the task when the level of the nonfocused stream increased.

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NOTES

1. We adopt the term *stream* to refer to each of the tempo/frequency combination subsequences making up the multistream sequence. We presume that the percept corresponds to this physical description of the stimuli, although recent data from our laboratory suggest that this may not always be the case.

2. Tests for homogeneity of variance revealed no significant deviations of variance, confirming the validity of the ANOVAs.

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