AD-A135 905 PATTERN-DIRECTED ATTENTION IN UNCERTAIN FREQUENCY DETECTION(U) CATHOLIC UNIV OF AMERICA WASHINGTON D C HUMAN PERFORMANCE LAB J H HOWARD ET AL. 14 OCT 83 1/1

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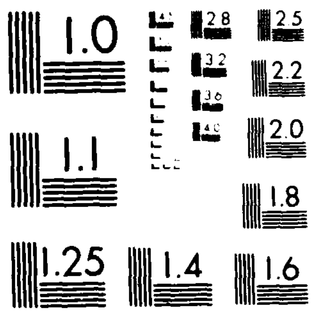

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PATTERN-DIRECTED ATTENTION IN UNCERTAIN FREQUENCY DETECTION

James H. Howard, Jr., Alice J. O'Toole, Raja Parasuraman, and Kevin B. Bennett

ONR CONTRACT NUMBER N00014-79-C-0550

Technical Report ONR-83-22

Human Performance Laboratory

The Catholic University of America

October, 1983

Unclassified

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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER ONR-83-22	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) Pattern-Directed Attention in Uncertain Frequency Detection	5. TYPE OF REPORT & PERIOD COVERED Technical Report
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) James H. Howard, Jr., Alice J. O'Toole, Raja Parasuraman, and Kevin B. Bennett	8. CONTRACT OR GRANT NUMBER(s) N00014-79-C-0550
9. PERFORMING ORGANIZATION NAME AND ADDRESS The Catholic University of America Washington, D.C. 20064	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N 42; RR 042 09; RR 042 09 01; NR 196-159
11. CONTROLLING OFFICE NAME AND ADDRESS Engineering Psychology Programs, Code 442 Office of Naval Research Arlington, VA 22217	12. REPORT DATE 14 October, 1983
	13. NUMBER OF PAGES 33
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

auditory perception
auditory signal detection
probe-frequency method
selective attention
top-down processing
uncertain frequency detection

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The role of early pattern components as cues in uncertain frequency detection was investigated in four probe-signal experiments. Listeners heard consecutive presentations of a 12-tone pattern in a noise background. One presentation of the pattern was complete whereas the other was missing the eleventh(primary) tone. Listeners were required to indicate which presentation was complete. On 20% of the test trials, the eleventh →

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component of the complete pattern was replaced with one of four probe tones. The results indicated that listeners were more sensitive to the primary tone than to probe tones but this selective sensitivity changed on a trial-by-trial basis as a function of the attentional cues provided by early pattern components. The data suggested two cue functions: (1) an "informational" function in providing information regarding which primary tone is likely to occur on a given trial, and (2) a "frequency" function that "automatically" directs listening to an appropriate frequency range and narrows or "fine tunes" the listening band.

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Pattern-Directed Attention in Uncertain Frequency Detection

In a typical psychoacoustic detection task, listeners are required to listen for a pure tone in a background of noise. In the popular two-alternative forced-choice procedure a tone of known frequency occurs in one of two brief, clearly-demarked listening intervals on each trial. One variation of this "standard" procedure involves selecting the test tone from one of two or more frequencies which may or may not be known to the listener. This procedure introduces uncertainty regarding the tonal frequency which will occur on any given trial. The results of a number of these uncertain frequency experiments have revealed a small but consistent degradation of detection performance when compared to the standard or certain frequency task (Swets, 1963).

Most explanations of this finding assume that listeners have a limited-bandwidth listening or attention band. In the certain frequency case this band can be adjusted to match the known frequency of the test signal, whereas in the uncertain frequency case an optimal location for the listening band cannot be predicted for any given trial. The concept of an attentional band is related to Fletcher's (1940) classic notion of the critical band, but with an emphasis on central rather than peripheral factors in audition. As Swets and Kristofferson (1970, p. 350) have pointed out, attentional studies generally "...reflect the view that frequency selectivity is substantially under the intelligent control of the observer--their focus is on attention rather than on the basilar membrane."

The present study reflects this emphasis. Four experiments are reported which investigate the cues listeners use to adjust their attentional band on a trial-by-trial basis to detect selected individual tones embedded within multi-tone patterns.

Uncertain frequency experiments. In an early experiment Tanner and Norman (1954) employed a four-interval forced choice method and found that performance fell to chance levels when the test signal was shifted from a known frequency to another frequency without informing the listeners. Greenberg and Larkin (1968) introduced a related probe-signal method in which listeners first learn to detect signals of a single primary frequency in a standard detection task. After this, other signals of different probe frequencies were presented on a small proportion of the trials (e.g., 20%). Their findings, similar to those of Tanner and Norman (1954), revealed that detection of unexpected probe frequencies which differed from the primary frequency by more than approximately 150-200 Hz was at a chance level. Greenberg and Larkin (1968) argued that the probe-signal method may be used to estimate the shape and width of the listening band; however, others have suggested that the method may be limited for characterizing the precise shape of the auditory filter (Patterson & Nimmo-Smith, 1980). Macmillan and Schwartz (1975) have used the probe-signal method successfully to demonstrate concurrent two-channel listening in uncertain frequency detection. Other studies have demonstrated that uncertain frequency will lead to degraded performance when compared to a single frequency condition even if the listeners are aware that more than one signal can occur (Creelman, 1960; Green, 1961).

Theories of uncertain frequency detection. Most theoretical accounts of the uncertain frequency effect have assumed that listeners use either single or multiple listening bands. The single-band approach, introduced by Tanner, Swets, and Green (1956, as cited in Swets, 1963), assumes that listeners employ a single listening band which must include the test signal frequency for detection to occur. In an uncertain frequency experiment the listening band must be swept across a range of frequencies or between two known frequencies and consequently signals will be missed.

On the-other hand, the multiple band approach, introduced by Green (1958) and modified by Creelman (1960), assumes that listeners base their decision on the combined outcomes of several listening bands positioned at different frequencies. Different methods are assumed for combining the multiple filter outputs, but all these models assume that the detectability of an individual tone will decrease as the number of listening bands increases.

Empirical evidence has been reported to support both the single-band (Swets & Sewall, 1961; Swets, Shipley, McKey, & Green, 1959) and the multiple-band approaches (Creelman, 1960; Green, 1961; Macmillan & Schwartz, 1975). In general, the two views are difficult to distinguish empirically, and Green (1961; Green & Weber, 1980) has argued that uncertain frequency effects are generally smaller than would be predicted by either theory. According to Green (1961), this latter finding may simply reflect the fact that considerable subjective uncertainty exists in even the standard detection task thereby lowering performance relative to a certain frequency condition. Other evidence suggests that either a single- or a multiple-band listening strategy may be used depending on the task context and the individual observer (Swets, 1963; Green, 1961).

In a more recent paper, Johnson and Hafter (1980) proposed an extension of the traditional multiple-band model. Their model assumes that two factors are under listener control and can influence performance: (1) the number of listening bands, and (2) the bandwidth of the listening band(s). The first factor is influenced by the listener's expectations regarding the number and frequency of signals likely to occur, whereas the second factor is influenced by the accuracy of the listener's knowledge regarding the test frequencies. Overall, the listener's attentional strategy determines the trade off which will occur between the two factors. This model incorporates earlier ideas regarding adjustable filter bandwidth (Swets, 1963; Sorkin, Pastore, & Gilliom, 1968), and reflects properties of both the single- and the multiple-band models. Listeners may choose to monitor only a single narrow band under conditions of low frequency uncertainty or one or more broad bands when signal uncertainty is high.

Control of attention in auditory detection. In many uncertain frequency detection studies the listener's attention is influenced by overall properties of the signal probability distribution (Swets, in press). In other words, listeners tend to listen for high probability signals rather than for low probability signals. Other studies have used explicit signal cues to provide information regarding the likely signal frequency (Swets & Sewall, 1961; Gilliom & Mills, 1976; Kinchla, 1973).

For example, several studies have demonstrated improved performance under uncertain frequency conditions when a tone of the same frequency as the test tone preceded the listening interval (Swets & Sewall, 1961; Gilliom & Mills, 1976; Johnson & Hafter, 1980). Cues of this sort have been termed frequency cues (Gilliom & Mills, 1976) since the cue itself can serve as a frequency model. On the other hand, frequency cues also serve as informational cues since they inform the listener of the likely frequency of the test tone. Swets and Sewall (1961) have shown that pure informational cues (lights) can be as effective as tonal frequency cues in enhancing performance in uncertain frequency tasks. The results of these cue studies suggest that listeners are able to adopt a listening strategy which permits trial-by-trial variations in their attentional focus.

The present study. The present study investigates the potential frequency and informational cue value of early components in simple tonal patterns when listeners are required to detect the presence of later elements. Watson and his associates have shown in a series of same-different pattern discrimination experiments that listeners are better able to resolve individual pattern elements under conditions of low stimulus uncertainty than under high uncertainty conditions (Watson & Kelly, 1981). Uncertainty was reduced in their experiments by using either highly familiar tonal patterns or by using test components of predictable frequency. Jones, Boltz, and Kidd (1982) have also shown that both the melodic (frequency) and rhythmic (temporal) properties of simple patterns can influence a listener's attention to embedded pattern components. These findings suggest that early pattern components will serve as significant attentional cues for detecting subsequent pattern components.

Four probe-signal experiments are reported which examine this possibility. In each experiment listeners are presented with pairs of twelve-element tonal patterns. On each trial one of two patterns is complete whereas the other has a gap in place of the eleventh component. Listeners are required to report which of the two was complete. After training, the high probability or primary signal in the complete pattern is replaced by one of several probe frequencies on a small percentage of the trials (20%). This method parallels the probe-signal experiments summarized previously, but with the to-be-detected tones occurring within a pattern context. Since either of two different patterns can occur on any trial, the utility of the first ten components in directing the listener's attention to the proper frequency can be determined.

In the first experiment, high and low frequency "patterns" of a single repeating frequency were used so that early pattern components could serve as same-frequency attentional cues for the detection of a later element. The early components in this experiment serve both as informational cues, since the early tones are perfectly correlated with the test frequency for that pattern, and as frequency cues since they are the same frequency as the test element. In the second experiment, patterns of increasing and decreasing frequencies were presented. Early components of these patterns serve primarily as informational cues rather than frequency cues in directing individuals to listen at the appropriate frequency. Experiments 3 and 4 used patterns of rising and falling frequency as in Experiment 2, but with an "off-pattern" high probability primary signal. In these experiments the pattern context provides an inappropriate frequency cue for the primary test signal. In Experiment 3, listeners must ignore the pattern context to focus on a single primary frequency common to both patterns, whereas in Experiment 4 the early pattern components must be used only as informational cues to attend selectively to that appropriate frequency on a trial-by-trial basis.

Experiment 1

Method

Participants. Four student and staff volunteers between the ages of 20 and 35 participated in the experiment. None reported any history of hearing disorders.

Stimuli. The stimuli consisted of two 12-tone patterns of pure tones into which a test tone would be inserted. The pattern and test tones were selected from a set of five pure tone signals with frequencies of 700, 1150, 1600, 2050, and 2500 Hz. The tones were 100 ms in duration with 5 ms onset/offset ramps to eliminate audible clicks. The energy levels of the five tones were adjusted to yield equally detectable signal-to-noise ratios using the following equation from Green, McKey & Licklider (1959): $10 \log(E/No) = 2(f/fc) + 16.6$ dB, where E = signal energy, No = noise power density, f = signal frequency, and fc = 1000 Hz. With this adjustment the signal presentation levels ranged from approximately 63.6 dB SPL (700 Hz) to approximately 67.2 dB SPL (2500 Hz) in equal steps of .9 dB. The tones were presented in a continuous noise background (400-3500 Hz).

The two constant patterns were constructed of 12 repetitions of either the 1150 Hz tone (low pattern) or the 2050 Hz tone (high pattern) with an inter-tone-interval of 20 ms. The 1150 (2050) Hz tone was the high probability primary test signal for the low (high) constant pattern and the remaining four tones were the low probability probe test signals. The two patterns and the five test signals used in this experiment are shown schematically in Figure 1a.

Insert Figure 1 here

On every trial, either the high or the low frequency pattern was presented twice, once as a complete pattern and once as an incomplete pattern. The incomplete pattern had a 100 ms delay substituted for the eleventh tone presentation, whereas the complete pattern had either the primary or a probe signal at this test position. On the practice trials only the primary tone occurred at the test position (i.e., 1150 Hz for the low pattern and 2050 Hz for the high pattern). The practice trials began with a signal-to-noise ratio of 28.6 dB (1000 Hz) which was reduced gradually to the test level of 18.6 dB (1000 Hz). During the two test blocks the eleventh pattern position contained the primary tone on 80% of the trials and a probe tone on the remaining 20% of the trials. Consequently, each of the four probes for each pattern occurred on eight trials, whereas the primary occurred on 128 trials in each test block.

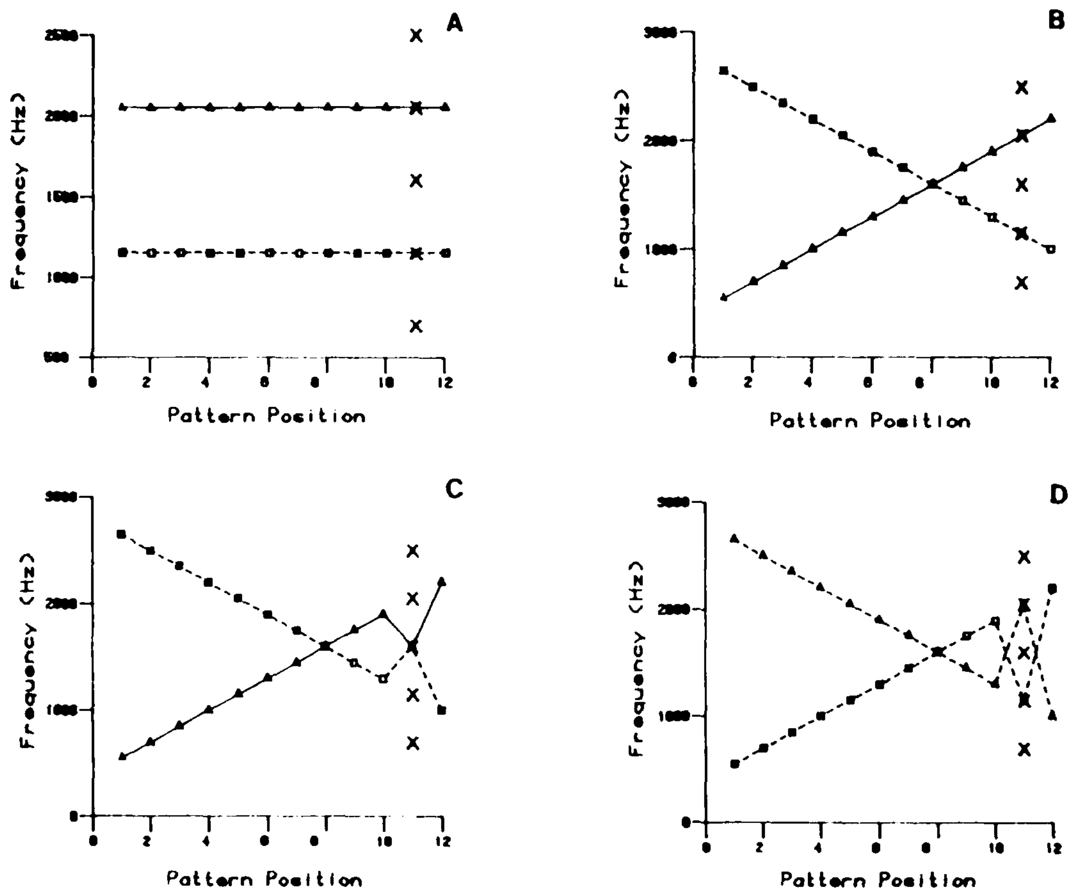

Figure [illegible] [illegible]ematic [illegible] of the [illegible] patterns and test signals for Experiment [illegible] A through [illegible]

Apparatus. All experimental events were controlled by a general-purpose laboratory computer. The tones were synthesized using standard digital techniques. They were output on a 12-bit digital-to-analog converter at a sampling rate of 10 kHz, low-pass filtered at 4 kHz (Khron-Hite Model 3550), attenuated (Charybdis programmable attenuator), and presented monaurally (right ear) over a calibrated TDH-49 headphone with an MX-41/AR cushion. The noise was produced by a broadband generator (Brüel & Kjaer Model 1402), bandpass filtered (Khron-Hite Model 3750) and mixed with the tones using a laboratory constructed passive mixer. Verbal prompts were presented on a video monitor in the double-walled testing booth (Industrial Acoustics), and a solid-state keyboard was used for listener responses.

Procedure. Listeners were tested individually over five days. A two alternative forced-choice task was used on each day. On the first day listeners were instructed that they would be hearing pairs of simple patterns on each of a series of trials. One of these patterns would be complete, whereas the other would have a single component tone missing. They were told that their task would be to determine which of these otherwise identical patterns was complete. Listeners were also told that the patterns would be played in a steady noise to make the task more difficult; however, to permit familiarization with the task, the patterns would initially be relatively easy to hear.

On each of the five days listeners received three blocks of trials, one practice block (100 trials) and two test blocks (160 trials in each).

Each listener had 500 practice trials and 1600 test trials in all. The order of presentation was determined randomly both within (order of complete and incomplete patterns) and across (pattern and test frequency) trials within each block.

Results and Discussion

The percentage of correct responses was determined for each test frequency for each pattern and listener in the experiment. Percent correct provides a bias-free estimate of sensitivity because a two-alternative forced-choice procedure was used. The results of this analysis are shown collapsed across the four listeners in Figure 2 for both the high and low frequency patterns.

Insert Figure 2 here

A two-way analysis of variance (pattern by frequency) with repeated measures on both factors was carried out on these data. This analysis revealed significant main effects of pattern, $F(1,3)=10.86$, $p<.05$, and frequency, $F(4,12)=3.55$, $p<.05$, and a significant pattern by frequency interaction, $F(4,12)=8.88$, $p<.01$. To investigate the interaction further, the simple effects of pattern were determined for each of the five test frequencies. A significant simple effect of pattern was observed at the two primary frequencies of 1150 Hz, $F(1,3)=963.60$, $p<.05$, and 2050 Hz, $F(1,3)=651.60$, $p<.05$, and at the 2500 Hz probe frequency, $F(1,3)=836.40$, $p<.05$. The simple effects of pattern were not significant for either the

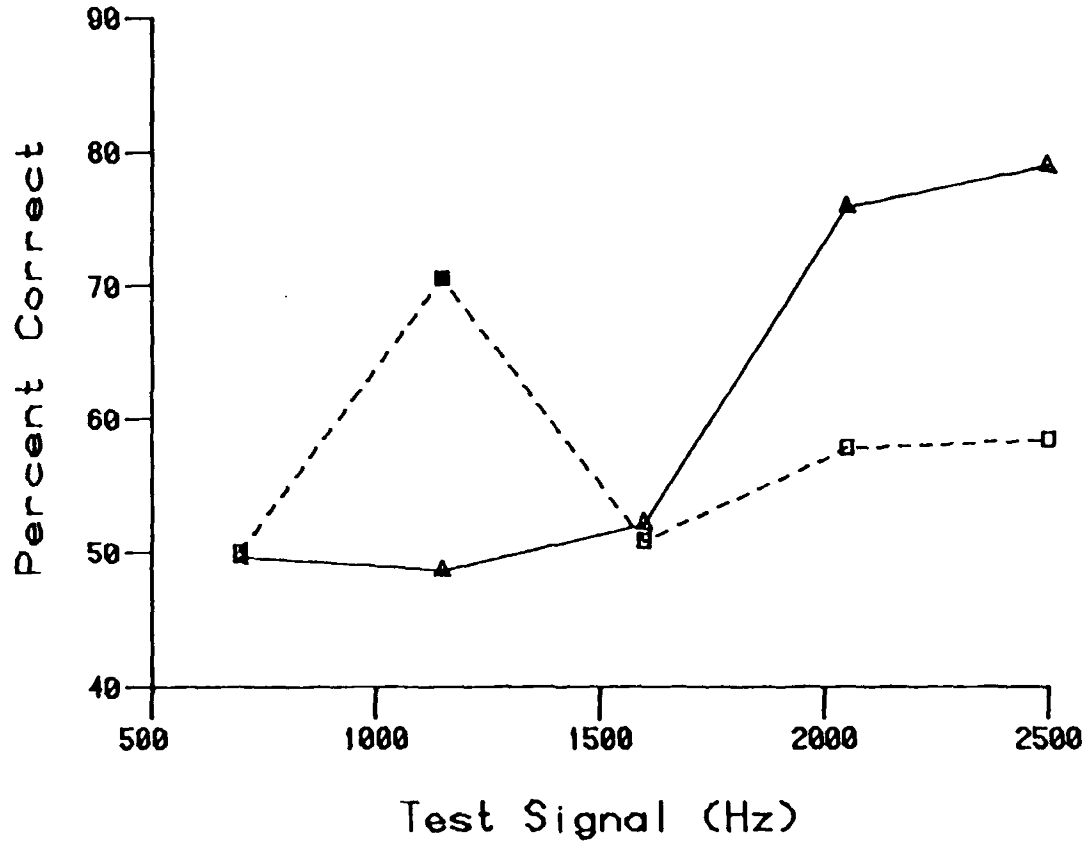

Figure 2. Mean percent correct collapsed across the four listeners of Experiment 1 at each test frequency for both the high (solid line; triangles) and low (dashed line; squares) patterns. Filled symbols show the high-probability primary frequency for each pattern.

700 Hz probe, $F(1,3)<1.0$, or the 1600 Hz probe, $F(1,3)<1.0$. As is evident in Figure 2, performance was substantially better on the high-probability primary test signals for each pattern than it was on the low-probability probes. This suggests that the listeners were able to use the initial segment of the pattern to attend selectively to the likely test frequency for that pattern, and that this selection occurred on a trial-by-trial basis. The only exception to this was on high-pattern trials where the 2500 Hz probe was highly detectable (79% correct). This unexpected finding suggests that listeners may have used an unusually broad listening band on the high-pattern trials, an interpretation consistent with the constant-Q properties assumed for the critical band. This possibility will be considered again in Experiment 2.

Experiment 2

Overall, the results of the first experiment are consistent with the hypothesis that listeners can use early pattern components as frequency and/or informational cues to shift their listening band to high probability test frequencies on a trial-by-trial basis. In the second experiment patterns of rising and falling pitch were used in which the early pattern components were at frequencies either below (rising pattern) or above (falling pattern) the optimal listening frequency. Hence, the early pattern components should serve primarily as informational cues. If pattern-dependent cue effects are obtained in this experiment then the value of early pattern components as informational cues for trial-by-trial selective listening will have been established.

Method

Participants. Four student and staff volunteers between the ages of 25 and 33 participated in the experiment. None reported any history of hearing disorders, and none participated in Experiment 1.

Stimuli. A set of 15 pure tones ranging in frequency from 550 Hz to 2650 Hz in equal steps of 150 Hz (including the five described for Experiment 1) were used to construct two twelve-tone patterns. For the rising pattern the tones between 550 Hz and 2200 Hz were presented in ascending order, whereas for the falling pattern the tones between 2650 Hz and 1000 Hz were presented in descending order. As in the previous experiment, all tones were 100 ms in duration with a 5 ms onset/offset ramp, and the patterns had an inter-tone-interval of 20 ms. The intensity levels of all 15 tones were adjusted to be equally detectable in noise as in Experiment 1. The two patterns are shown schematically in Figure 1b. The primary (2050 Hz for the rising pattern and 1150 Hz for the falling pattern) and probe test signals were presented in the eleventh pattern position and were identical to those used in Experiment 1. The continuous noise background was also identical to that used in Experiment 1.

Apparatus. The apparatus was identical to that used in Experiment 1.

Procedure. The procedure was the same as in Experiment 1 except that participants were instructed that the patterns would be either rising or falling in pitch.

Results and Discussion

A bias-free percentage of correct responses was determined for each test frequency for each pattern and listener in the experiment. These data are shown collapsed across the four listeners in Figure 3 for both the rising and falling patterns.

Insert Figure 3 here

A two-way analysis of variance (pattern by frequency) with repeated measures on both factors was performed on the data. This revealed a significant main effect of frequency, $F(4,12)=3.27$, $p<.05$, and a significant pattern by frequency interaction, $F(4,12)=6.45$, $p<.01$. The main effect of pattern was not significant, $F(1,3)<1.0$. An analysis of the simple effects of pattern at each test frequency revealed significant effects at the 1150 Hz primary, $F(1,3)=20.71$, $p<.01$, and at the 2050 Hz primary, $F(1,3)=26.02$, $p<.01$, but no significant simple effect of pattern at any of the probe test frequencies, $F(1,3)<1.0$ (700 Hz), $F(1,3)=1.02$, $p>.05$ (1600 Hz), and $F(1,3)=3.67$, $p>.05$ (2500 Hz).

Inspection of Figure 3 suggests a finding very similar to that observed in the results of Experiment 1. Specifically, the high-probability primary test signals were detected more readily than were the low-probability probes. Furthermore, since the effect was pattern specific, it is clear that listeners were adjusting their listening band to "appropriate" frequencies on a trial-by-trial basis. These findings also

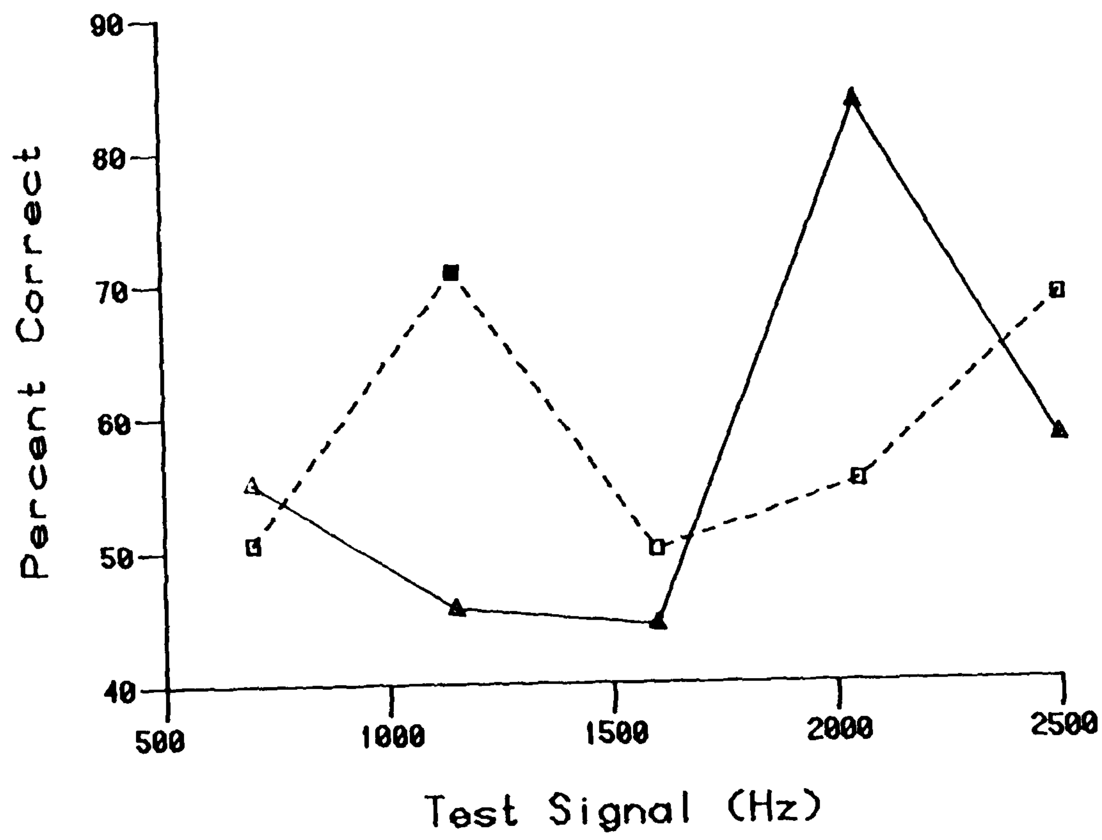

Figure 3. Mean percent correct collapsed across the four listeners of Experiment 2 at each test frequency for both the rising (solid line; triangles) and falling (dashed line; squares) patterns. Filled symbols show the high-probability primary frequency for each pattern.

demonstrate the informational value of the initial pattern components since these tones were not at the primary test frequency. If the average performance advantage for the primary test signals over the probe signals is taken as a measure of "cue effectiveness," then the rising and falling patterns used in this experiment (23.6% primary advantage) were as effective as the constant-frequency patterns used in the first experiment (23.0% primary advantage).

As in Experiment 1, the highest frequency probe signal (2500 Hz) was detected more often than any of the other probes (63.4% vs 50.1%). However, unlike the results of the first experiment, the present results do not reveal a differential sensitivity to this probe when the primary is also high frequency (2050 Hz). This suggests that any special status attributable to this probe may be due to a very small and theoretically-uninteresting overall sensitivity difference which was not eliminated by our efforts to equate sensitivity across frequency (see method, Experiment 1).

Experiment 3

Although the results of Experiment 2 indicate that off-primary frequencies can serve effectively as selection cues for a primary frequency, the monotonicity of the rising and falling patterns may have induced a frequency-directed listening strategy. In other words, in both Experiments 1 and 2, listeners could simply track the frequencies of the initial pattern components to direct their listening band to the appropriate frequency. Such frequency-directed attention was examined further in Experiment 3. Patterns with initially rising or falling pitch were used as in Experiment 2, but a single high-probability primary test signal was used at an off-pattern frequency either below the on-pattern frequency for the rising pattern or above it for the falling pattern. Under these conditions a listener need only listen at the primary frequency on every trial regardless of the pattern context. If the listener's attention is directed automatically to the on-pattern frequency by the rising and falling patterns, then the performance advantage revealed for the primary signal in the first two experiments should not occur. Rather, the results should be similar to those of Experiment 2 with the on-pattern frequencies being most readily detectable. On the other hand, if listeners are able to ignore the pattern context and direct their attention to the constant off-pattern primary frequency, then a performance advantage should be found for the primary frequency.

Method

Participants. Six student volunteers between the ages of 18 and 22 participated in the experiment. None reported any history of hearing disorders; however, two listeners were dropped from the experiment when they were unable to perform above chance on the preliminary practice trials. None of the participants served in either of the previous experiments.

Stimuli. Rising and falling patterns were constructed from the tone set used in Experiment 2. For both patterns, however, the 1600 Hz tone was used as the high-probability primary test signal, with the 700, 1150, 2050, and 2500 Hz tones serving as low-probability test probes. As in the previous experiments only the primary probes were presented during practice. The stimuli were otherwise identical to those used in Experiment 2. The two stimulus patterns are shown schematically in Figure 1c.

Apparatus. The apparatus was identical to that used in Experiment 1.

Procedure. The procedure was the same as that used in Experiment 1 except that listeners were told that the patterns would be either generally rising or generally falling in pitch.

Results and Discussion

A bias-free percentage of correct responses was determined for each test frequency for each pattern and listener in the experiment. These data are shown collapsed across the four listeners in Figure 4 for both the rising and falling patterns.

Insert Figure 4 here

A two-way analysis of variance (pattern by frequency) with repeated measures on both factors revealed a significant main effect of frequency, $F(4,12)=7.59$, $p<.01$. Neither the main effect of pattern $F(1,3)=1.10$, $p>.05$, nor the pattern by frequency interaction, $F(4,12)<1.0$, was

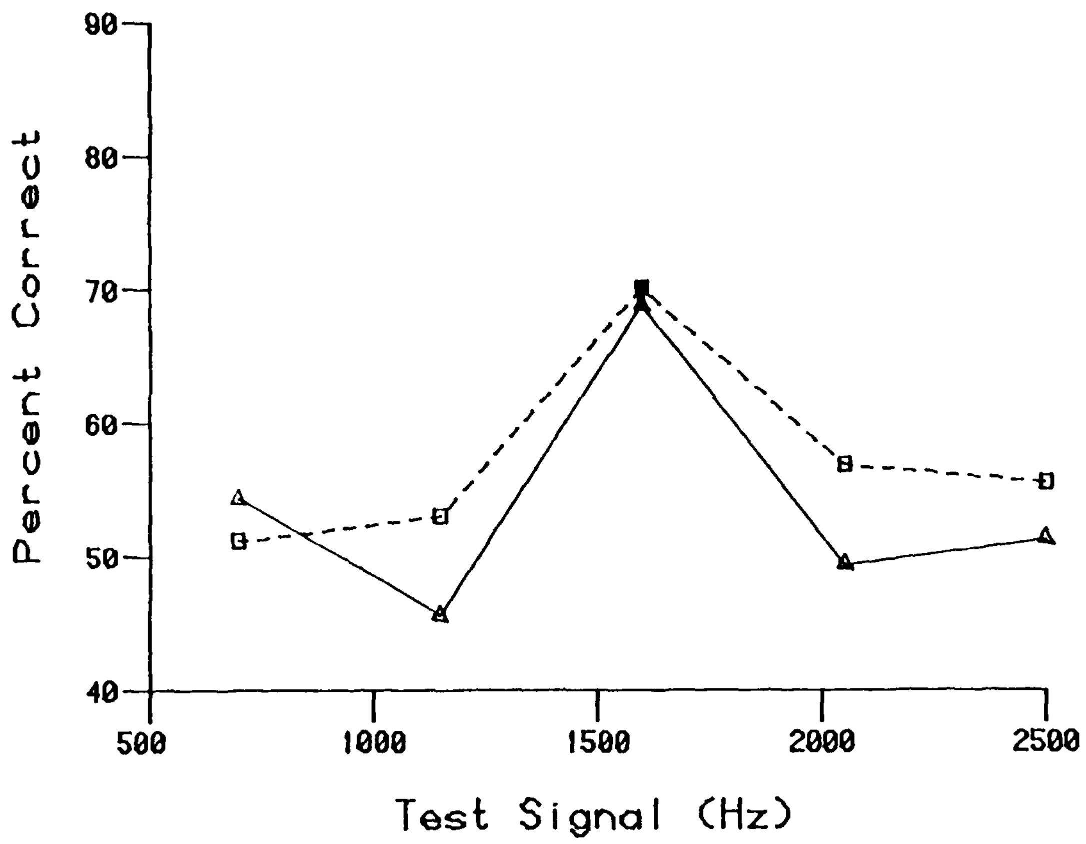

Figure 4. Mean percent correct collapsed across the four listeners of Experiment 3 at each test frequency for both the rising (solid line; triangles) and falling (dashed line; squares) patterns. Filled symbols show the high-probability primary frequency for each pattern.

significant.

As may be seen in Figure 4, the high probability off-pattern primary was more detectable than the on-pattern probes for both the rising and the falling patterns. This indicates that listeners were able to center their listening bands at the off-pattern primary frequency despite the conflicting frequency context provided by the patterns. Nevertheless, the average performance advantage for the primary over the probe signals (17.2%) was somewhat smaller in this experiment than in the first two experiments (23.0% and 23.6%, respectively). Although not definitive, this suggests that the pattern context in the present experiment may have disrupted the listeners' attentional strategy. An automatic, frequency-directed listening seems unlikely, however, since the rising and falling patterns did not influence sensitivity to the on-pattern probes differentially.

Experiment 4

The results of Experiment 3 revealed that listeners generally are able to dismiss a pattern frequency context when it is an inappropriate attentional cue for the task. Experiment 4 was designed to investigate the ability of listeners to use early pattern components selectively as informational cues for off-pattern primary test signals. Rising and falling patterns were used as in Experiments 2 and 3. For this experiment, however, the high-probability primary tone for the rising pattern was the on-pattern frequency for the falling pattern and the primary for the falling pattern was the on-pattern frequency for the rising pattern. If listeners are able to use the early pattern components only as informational cues then a pattern-specific performance advantage should be obtained for the primary frequencies. On the other hand, if frequency-directed listening occurs or the inappropriate pattern context is generally disruptive as in Experiment 3, then the primary advantage should be absent or reduced in magnitude.

Method

Participants. Four student volunteers between the ages of 18 and 22 participated in the experiment. None reported any history of hearing disorders, and none served in any of the previous experiments.

Stimuli. Rising and falling patterns were constructed from the tone set used in Experiment 2. For the rising (falling) pattern, however, the 1150 (2050) Hz off-pattern tone was used as the high-probability primary test signal. The low-probability test probes were the 700, 1600, 2050, and 2500 Hz tones for the rising pattern and the 700, 1150, 1600, and 2500 Hz tones for the falling pattern. These patterns are shown schematically in Figure 1d. As in the previous experiments only the primary probes were presented during practice.

Apparatus. The apparatus was identical to that used in Experiment 1.

Procedure. The procedure was the same as that used in Experiment 3.

Results and Discussion

A bias-free percentage of correct responses was determined for each test frequency for each pattern and listener in the experiment. These data are shown collapsed across the four listeners in Figure 5 for both the rising and falling patterns.

Insert Figure 5 here

Examination of this figure suggests pattern-specific differences in sensitivity. However, the performance advantage obtained, (8.6%) is considerably smaller than that observed in the earlier experiments (23.0%, 23.6%, and 17.5%, for Experiments 1, 2, and 3, respectively). A closer examination of the these data revealed that unlike the earlier experiments, one listener had a pattern of results opposite that of the other three. This individual showed increased sensitivity to the low-probability, on-pattern probes and chance performance for the high-probability, off-pattern primaries. This result suggests that she employed a frequency-directed listening strategy. The data collapsed across the remaining three consistent listeners are shown in Figure 6.

Insert Figure 6 here

A two-way analysis of variance (pattern by frequency) with repeated

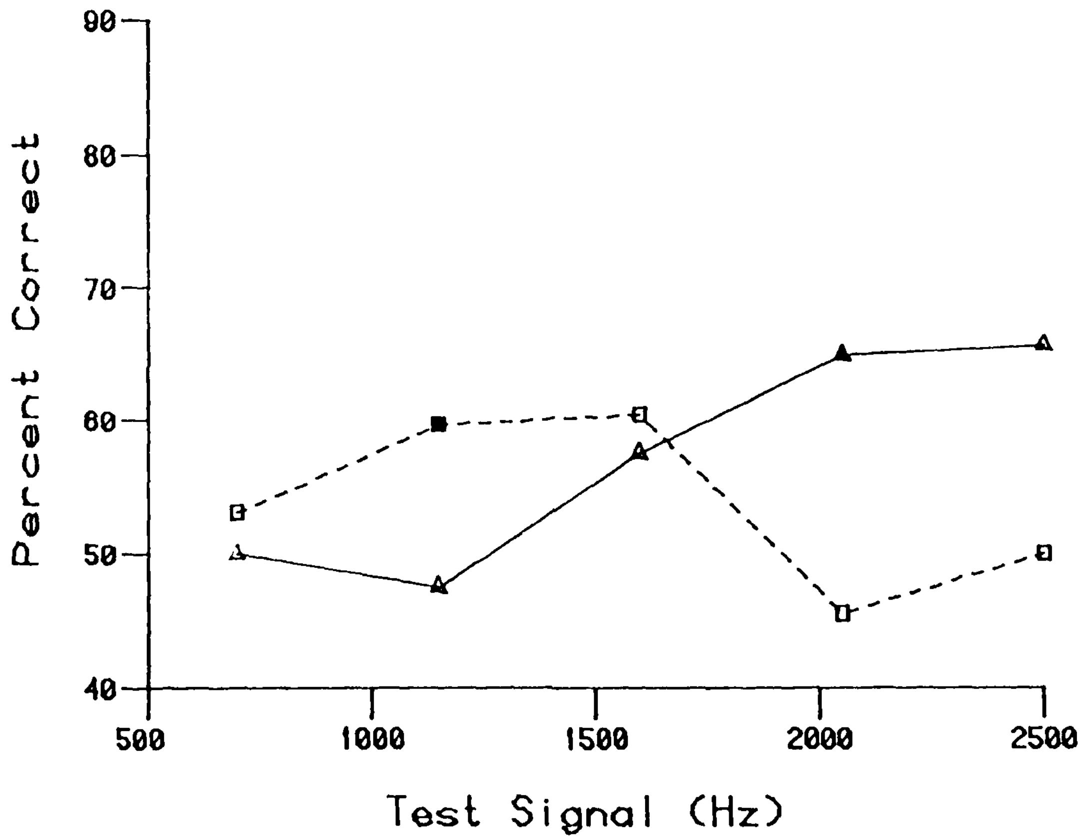

Figure 5. Mean percent correct collapsed across the four listeners of Experiment 4 at each test frequency for both the falling (solid line; triangles) and rising (dashed line; squares) patterns. Filled symbols show the high-probability primary frequency for each pattern.

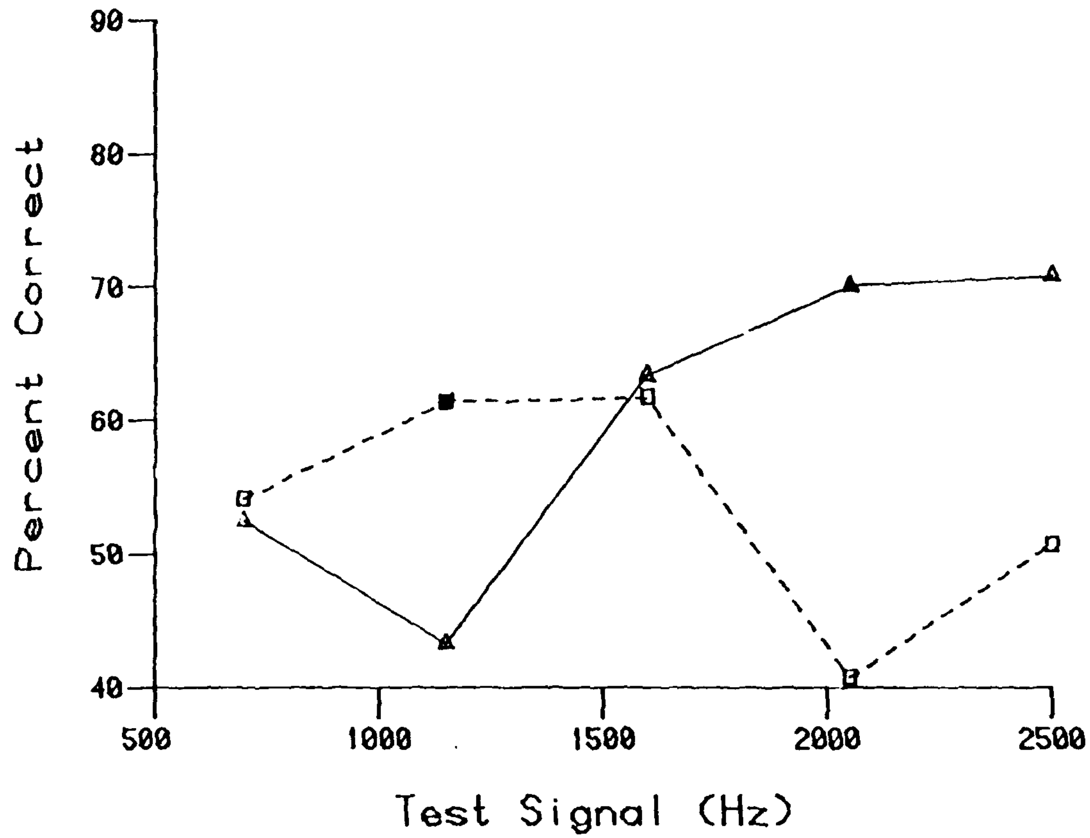

Figure 6. Mean percent correct collapsed across the three consistent listeners of Experiment 4 at each test frequency for both the falling (solid line; triangles) and rising (dashed line; squares) patterns. Filled symbols show the high-probability primary frequency for each pattern.

measures on both factors was performed on these data. This analysis showed a significant main effect of pattern, $F(1,2)=20.57$, $p<.05$, and a significant pattern by frequency interaction, $F(4,8)=12.70$, $p<.01$. No reliable main effect of pattern, $F(4,8)=1.92$, $p>.05$, occurred. An analysis of the simple effects of pattern at each test frequency revealed significant differences at the two primary frequencies, $F(1,3)=34.72$, $p<.01$ (1150 Hz primary for the rising pattern) and $F(1,3)=90.50$, $p<.01$ (2050 Hz primary for the falling pattern), and at the highest probe frequency $F(1,3)=51.17$, $p<.01$. The pattern effect did not approach significance at either of the other probe frequencies, $F(1,3) < 1.0$ (700 Hz and 1600 Hz).

As may be seen in Figure 6, sensitivity was greater for the high-probability, but off-pattern primary for both the rising (1150 Hz) and the falling (2050 Hz) patterns. This indicates that the listeners were able to use the early pattern components as informational cues despite the misleading frequency direction of the pattern. Nevertheless, a weaker cue advantage occurred, (11.1%) than in the first three experiments (23.0%, 23.6%, and 17.2%, respectively), suggesting that the frequency context provided by the early pattern components was not ignored totally. This is consistent with the results of Experiment 3 in which an inappropriate frequency context disrupted single-frequency listening. In the present experiment, disruption was greater for either or both of two reasons: (1) unlike Experiment 3, the present experiment required trial-by-trial attentional shifting, (2) in the present experiment, the high-probability primaries were further off the frequency context (differences of 900 Hz vs. 450 Hz) of the pattern than in Experiment 3. The greater sensitivity observed for the 2500 Hz probe during the high-frequency listening is consistent with the results of Experiment 1. This finding, together with the relatively high sensitivity to the central 1600 Hz probe for both patterns (62.5%), suggests that listeners were using a broad listening band in the present experiment. Overall, then, it appears that although most listeners were able to use early pattern components as informational cues, the misleading frequency context provided by these tones led to a very poor tuning of the attentional filter. The inability of one listener to avoid on-pattern listening further illustrates this point.

General Discussion

Overall, the results of this study support several conclusions regarding the role of *early pattern components* as cues in uncertain frequency detection. First, the results of Experiments 1, 2, and 4 support the conclusion of earlier studies that listeners can shift their attention to likely frequencies on a trial-by-trial basis. Second, it is clear from these experiments that early pattern components can serve as cues to reduce uncertainty for the detection of later pattern elements.

Third, the findings also suggest that it is necessary to distinguish two functions for listening cues in this context. On the one hand, the cues in the three uncertain-frequency experiments (1, 2, and 4) served an informational function to reduce uncertainty regarding the likely test frequency on any trial. On the other hand, Experiments 3 and 4 revealed a distinct frequency-cueing function of the early pattern cues. In the certain frequency task used in Experiment 3, the rising and falling pattern contexts provided an inappropriate frequency cue which degraded listening performance. Furthermore, in Experiment 4 where only the informational content of early pattern components was relevant for selective listening, the conflicting frequency cues provided by these components were also disruptive. One of the four listeners in this experiment ignored the informational content of the early components entirely and listened at the inappropriate on-pattern frequencies cued by the rising and falling tonal patterns. The remaining listeners were able to use the informational cues but with only a poorly-tuned, broad listening band.

Fourth, the results of both Experiments 3 and 4 suggest that listeners are unable to ignore completely the frequency content of cues even when the signal probabilities make it inappropriate as a cue. This automatic processing of frequency information is also supported by the results of a sequential analysis carried out on uncertain frequency detection data by Swets, Shipley, McKey, and Green (1959). This analysis revealed a greater sensitivity to signals which were detected correctly on the previous trial, suggesting that recently experienced tones serve as implicit frequency cues. A similar result was found in a sequential analysis carried out on the data of the three uncertain frequency experiments in the present study. In all three experiments, listeners were more likely to detect tones which were heard on the previous trial than tones which were missed on the previous trial (.74 vs .71, .75 vs .69, and .64 vs .60 for Experiments 1, 2, and 4, respectively). This is also consistent with the finding of Johnson and Hafter (1980) that tonal cues which matched the test frequency led to better detectability than cues which did not match the test frequency.

These conclusions may be related to the two-factor theory of uncertain frequency detection presented by Johnson and Hafter (1980). They argue that two factors, (1) the number of listening bands, and (2) the bandwidth of these band(s), influence performance in uncertain frequency detection. It is possible that the informational function of listening cues influences the first of these factors. Specifically, the cue provides information regarding the number and location of bands to be monitored. In contrast, the frequency function of cues may influence the second of these factors. That is, appropriate frequency contexts which either match the test frequency or which are directed toward the test frequency allow finer tuning (i.e., a narrower bandwidth) than inappropriate frequency contexts. Although speculative without further research, the results of the present study suggest that the number and location of listening bands is under direct listener control, but the bandwidth factor is influenced by relatively automatic processes which may not be under direct listener control.

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Acknowledgements

The authors thank Darlene V. Howard and John J. O'Hare, the contract monitor, for their comments on an earlier version of the manuscript. Requests for reprints should be addressed to James H. Howard, Jr., Human Performance Laboratory, The Catholic University of America, Washington, D. C. 20064

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