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Allocating attention to frequency regions

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Three experiments were conducted to determine whether attention may be allocated to a specific frequency region. On each trial, a frequency cue was presented and was followed by a target tone. The cue indicated the most likely frequency of the forthcoming target about which the listeners were required to make a duration judgment. It was reasoned that if listeners are able to allocate attention to the cued frequency region, then judgments of any characteristic of a tone of the cued frequency should be facilitated relative to tones of different frequencies. Results indicated that duration judgments were made more quickly and accurately when the cue provided accurate frequency information than when it did not. In addition, performance generally declined as the frequency separation between cue and target increased. These effects are interpreted as an indication that listeners may use a frequency cue to allocate attention to a specific frequency region and that, under these conditions, the shape of the attentional focus conforms to a gradient. The possible similarities of covert orienting mechanisms in vision and audition are discussed.

Human sensitivity to weak auditory signals has been studied extensively (see, e.g., Creelman, 1959; Green, McKey, & Licklider, 1959). Typically, listeners have been asked to detect the presence of a prespecified sine-wave tone embedded in a white noise background. The sound level at which reliable detection of this target is obtained has been used as the measure of the listener's sensitivity. However, several investigators have shown that subjects are better able to detect expected tones as opposed to unexpected tones. Greenberg and Larkin (1968) developed a probe-signal paradigm to assess the extent of this expectancy effect. Subjects were presented with two successive intervals, each filled with white noise. A pure tone signal was embedded within one of these intervals on every trial. The listeners were to indicate in which of the intervals the signal was presented. The subjects were led to expect that only signals of a particular frequency would be presented (this expected signal is often referred to as the *primary*). However, on a certain percentage of trials (typically about 30%), the signal presented was actually of an unexpected frequency (these unexpected signals are often referred to as *probes*). Greenberg and Larkin reported that detection was best for the primary, intermediate for probes within the critical band for the primary, and worst for probes outside of the critical band for the primary. This general method has been employed by many investigators to demonstrate the dependence of detection performance on expectancy and the primary-probe frequency relation (e.g., Dai, Scharf, & Buus, 1991; Johnson & Hafter, 1980; Macmillan & Schwartz, 1975; Penner, 1972; Scharf, Quigley, Aoki, Peachey, & Reeves, 1987; Schlauch & Hafter, 1991; Sorkin, Pastore, & Gilliom, 1968).

Recently, Scharf et al. (1987) offered an attentional explanation for this frequency sensitivity effect. Specifically, Scharf et al. suggested that

> the subject is able to make a choice among sensory events on the basis of special criteria, and readies the "filter" prior to stimulation so as to facilitate reception of relevant signals. This facilitation may even influence filtering in the cochlea, which implies fine-tuning in the sensory periphery. . . . The careful listener focuses attention on a particular frequency region. (p. 221)

In addition to the attentional explanation provided by Scharf et al., several other explanations, founded on the notion that the output of either one (or several) auditory filter(s) is (are) used by listeners to reach a decision (e.g., Green, 1958, 1961; Johnson & Hafter, 1980; Swets, 1963), have been proposed to account for the expectancy effect observed in frequency sensitivity experiments. It is important to note that these explanations all share the common assumption that the expectancy effect results exclusively from a differential sensitivity of the listener to tones of particular frequencies. However, because in some experiments listeners are not informed that signals other than the primary may be presented, it is possible that the expectancy effect may also indicate an influence of the experimental design on decision processes. This would appear to be of little consequence given that the use of a two-alternative forced choice paradigm is thought to be "an excellent technique for obtaining a measure of the observer's sensitivity which is uncontaminated by fluctuations in criterion" (Gescheider, 1985, p. 117).

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However, Greenberg and Larkin (1968) raised the possibility that response bias effects may contribute to the frequency sensitivity effect: "Whether the outlying frequencies are in fact not heard, or are heard but not considered signals, is a question for further investigation" (p. 1522).

Several reports suggest that decision processes are of little import, since frequency sensitivity effects may be obtained even when listeners are informed that both primary and probe signals may be presented (e.g., Dai et al., 1991; Scharf et al., 1987; Schlauch & Hafter, 1991). In contrast to these reports, some data reported by Scharf et al. suggest that decision processes may indeed play a significant role in frequency sensitivity effects. Scharf et al. reported the results of two control experiments in which listeners were informed that signals other than the probe could be presented on some trials. Detection was better for the primary than for the probes in both experiments, so the frequency sensitivity effect does not appear to be due only to decision processes. However, detection of the probes was more accurate (by about 10%) when listeners were informed of their presence than when they were not. Performance on the primary was, apparently, unchanged. This result suggests that, when the detection paradigm is employed, the specificity of selection attributed to an attentional mechanism may be influenced by factors other than perceptual sensitivity. Of course, if decision processes do play a role in frequency sensitivity, then there is no guarantee that this influence is completely eliminated by forewarning listeners that signals other than the primary will be presented occasionally. Indeed, as Kinchla (1990) has argued, "Even if a cue doesn't indicate which response is more likely, it can indicate which areas of an array should be given more weight when the decision process involves a weighted integration of impressions" (p. 728).

In the three experiments reported below, we sought to extend and substantiate earlier investigations by assessing frequency sensitivity within the context of an identification paradigm. All three experiments were based on the logical prediction that if listeners are able to orient attention to a cued frequency region, then perception of events that occur in an attended region should be facilitated in relation to perception of events that occur in unattended frequency regions. We reasoned that any response bias effects should be minimized in an identification paradigm wherein target sounds were presented above threshold and in isolation, and in which listeners knew that targets might be of several different frequencies.

EXPERIMENT 1

Experiment 1 was designed, primarily, to determine whether frequency sensitivity effects might be obtained with the use of an identification paradigm. Each trial began with a frequency cue followed by a target tone. Unlike in previous studies, the target was not embedded in noise but rather was presented in isolation. On all trials, the listeners were to determine whether the target tone was of a short or a long duration (according to prespecified examples). The duration judgment task was selected specifically because previous research has indicated it to be independent of frequency (e.g., Allan & Kristofferson, 1974; Woods, Sorkin, & Boggs, 1979). The frequency of the target tone was either the same as (a valid trial) or different from (an invalid trial) the frequency of the cue. On invalid trials, the frequency separation between cue and target was manipulated to allow assessment of whether duration discrimination depended on the similarity of cue and target frequencies.

Method

Subjects

Six students attending McGill University were paid for their participation. All had normal hearing, according to self-report.

Materials

Sounds. The MITSYN software package (Henke, 1990) was used to synthesize short- (50-msec), and long- (90-msec) duration sine-wave tone targets at frequencies of 600, 925, 1000, 1075, and 1500 Hz. An additional 1000-Hz tone, 65 msec in duration, was also synthesized. This tone sounded at the beginning of each trial and served to provide subjects with a cue of probable target frequency. All tones were synthesized with 5-msec linear onset/offset amplitude ramps to eliminate any onset or offset clicks. Sounds were presented at 65 dB SPL (C weighting) as measured by a GenRad sound level meter.

Computer System. The experiment was controlled by a 486/50 IBM-compatible computer. Sounds were presented binaurally through Sony MDR-V7 headphones.

Design and Procedure

Each trial began with the presentation of the 1000-Hz, 65-msec tone. This tone was designed to cue subjects to attend to the 1000-Hz frequency region. A target was presented 500 msec following this cue. On 75% of the trials, the frequency of the cue and that of the target were the same (valid trials). On the other 25% of trials, the frequency of the cue differed from that of the target (invalid trials). On invalid trials, the probability of a target at 600, 925, 1075, or 1500 Hz was .0625. Thus, on invalid trials, the frequencies of the cue and the target could be either near to (e.g., target = 925 Hz or 1075 Hz, hereafter designated invalid–near trials) or far from (e.g., target = 600 Hz or 1500 Hz, hereafter designated invalid–far trials) one another. The listeners were to indicate whether the target tone was short or long in duration. They responded by pressing "1" on a computer keyboard if they thought the target was short, and "0" if they thought the target was long. This mapping was reversed for half the subjects. The listeners initiated each trial by pressing the space bar after they had responded to the preceding trial.

At the beginning of the session, the short and long target tones of each fundamental frequency were presented so that the listeners might become acquainted with the sounds to be used in the experiment. The subjects next completed 96 practice trials (72 valid, 24 invalid) in order to become familiar with the requirements of the experiment. These practice trials were identical to the experimental trials, except that accuracy feedback was provided following each trial. Finally, listeners completed 480 (360 valid, 120 invalid) experimental trials. Testing was performed in a sound-attenuating chamber.

The listeners were asked to respond as quickly and accurately as possible. Median response times (RT), based on correct responses only, were calculated for each condition. The trials on which listeners responded more than 3,000 msec following the onset of the target were eliminated from all analyses in this experiment as well as in Experiments 2 and 3. This resulted in the elimination of approximately 1% of the responses in each experiment.

Results

A one-way within-subjects ANOVA (frequency separation) was performed for both RT and error data. These analyses revealed that both RT [$F(2,10) = 25.41$, $p < .001$] and errors [$F(2,10) = 10.49$, $p < .01$] declined as the frequency separation between the cue and the target increased. This effect was characteristic of all 6 subjects. Thus, as shown in Table 1, duration discrimination on valid trials was better than that on invalid–near trials ($p < .01$, by Tukey HSD test for both RT and errors).[1] Moreover, performance on invalid–near trials exceeded that for invalid–far trials ($p < .01$ for both RT and errors).

Discussion

The dependence of performance on the frequency relation between cue and target that was obtained in this experiment with the use of an identification paradigm serves to establish that a detection task is not a necessary condition for establishing frequency sensitivity effects. Moreover, the fact that a perceptual judgment independent of frequency may be facilitated or inhibited is consistent with the notion that attentional resources are allocated to a specific frequency region in response to the frequency cue. However, as was true in previous investigations of frequency sensitivity effects (see, e.g., Greenberg & Larkin, 1968; Scharf et al., 1987), the design of this experiment resulted in the target on valid trials being presented much more often (a ratio of 3:1) than the targets on invalid trials. Thus, listeners were more familiar with discriminating the duration of the valid target than they were with discriminating the duration of invalid targets. Although duration has been reported to be independent of frequency (e.g., Woods et al., 1979), it remains possible that differential familiarity with the target, not the allocation of attention to a cued frequency region, may have led to superior performance on valid trials. Experiment 2 was designed to eliminate this potential confound and to examine the time course of attention allocation.

EXPERIMENT 2

Subjects were again required to judge the duration of a brief tone that followed a frequency cue. However, in contrast to the design of Experiment 1, validly cued targets were equally likely to be of any one of three different frequencies. Invalidly cued targets were also equally likely to be of any of these three frequencies. This arrangement, then, ensured that listeners would be equally familiar with discriminating the duration of all targets used in the experiment. If performance is again found to depend on the relation between the frequency cue and the target tone, then converging evidence will be obtained that attention can be allocated to discrete frequency regions. Finally, we sought to determine whether the frequency sensitivity effect is dependent on the time available to allocate attention to the cued frequency region. To this end, the interval between the frequency cue and the target was manipulated (500, 1000, 1500 msec). If some time is required to fully engage attention at the cued frequency region, then the difference in performance on valid and invalid trials should increase with the time available to orient attention.

Table 1
Mean Reaction Time (in Milliseconds) and Percent Errors as a Function of Trial Type in Experiment 1

Trial Type	RT	% Errors
Valid	650	6.57
Invalid–near	745	10.83
Invalid–far	841	19.45

Method

Subjects

Twelve students attending McGill University were paid for their participation. All of them reported that they had normal hearing. None of these subjects had participated in Experiment 1.

Materials

Sounds. Short- (50-msec), and long- (100-msec) duration sinewave tones were synthesized at fundamental frequencies of 667, 1000, and 1500 Hz with the use of the MITSYN software package (Henke, 1990). The duration difference between targets (50 msec) was increased in this experiment from that used in Experiment 1 (40 msec). This manipulation was undertaken to increase the proportion of correct trials and thereby the stability of the mean RT estimates for conditions represented by only a few trials (e.g., invalid–near trials at the 500-msec interstimulus interval, or ISI). In addition, three frequency cues, each 75 msec in duration, were also synthesized at each of the fundamental frequencies. All tones were synthesized with 5-msec linear onset/offset amplitude ramps in order to eliminate any onset or offset clicks. Sounds were presented at 65 dB SPL (C weighting) as measured by a GenRad sound level meter.

Computer system. The computer system was the same as that used in Experiment 1.

Design and Procedure

A frequency cue was presented at the beginning of each trial. This cue indicated the frequency of the subsequent target tone accurately on 75% of the trials (valid trials) and inaccurately on 25% of the trials (invalid trials). As in Experiment 1, on invalid trials, the frequencies of the cue and the target could be either near to (e.g., cue = 667 Hz and target = 1000 Hz, invalid–near trials) or far from (e.g., cue = 667 Hz and target = 1500 Hz, invalid–far trials) one another. On invalid trials, the probability of a target with either of the two uncued frequencies was equal. This arrangement, then, allowed determination of whether performance would depend on cue validity and, further, whether performance on invalid trials would depend on the frequency separation between cue and target.[2] Finally, the ISI between the frequency cue and the target tone was varied (500, 1000, or 1500 msec). This manipulation was employed to elaborate the time course of any effect of the cue on performance on valid and invalid trials. This design, then, included nine unique combinations of frequency of cue, frequency of target (3), and ISI (3) for valid trials and 18 unique combinations of frequency of cue (3), frequency of target (2), and ISI (3) for invalid trials.

At the beginning of the session, the listeners were presented with the short and long target tones at each fundamental frequency so that they could become familiar with differentiating them. The subjects next completed 144 practice trials, consisting of 12 repetitions of the 9 unique valid trials and 2 repetitions of the 18 unique invalid trials. Accuracy feedback was given following each practice trial. Any practice trial to which a subject responded incorrectly was repeated at the end of the practice session. Thus, listeners were required to correctly answer (eventually) all of the 144 practice trials. Finally, listeners performed 432 experimental trials (324 valid and 108 invalid). The order of presentation for practice and experimental trials was completely random.

Results

A meaningful statistical analysis of the error data was impossible because of the low mean error rate (3.6%). However, as shown in Table 2, error rates generally followed the same pattern as did the RT data. The RT data are described in Figure 1.

Valid Trials

A one-way ANOVA (ISI) revealed that performance generally improved with increases in ISI [$F(2,22) = 29.73$, $p < .001$]. Further analyses revealed that this effect was due to a significant reduction in RT as ISI increased from 500 to 1,000 msec and from 1,000 to 1,500 msec ($p < .01$).

Invalid Trials

Performance on invalid trials was analyzed with a two-way ANOVA (frequency separation × ISI). The main effect of distance failed to attain statistical significance ($F < 1$). Thus, performance was independent of the frequency separation between target and cue. Performance did, however, improve with increases in ISI [$F(2,22) = 6.07$, $p < .01$]. Although neither the reduction in RT as ISIs increased from 500 to 1,000 msec nor that for the increase from 1,000 to 1,500 msec reached significance ($p > .05$), RT did decline significantly for the increase from 500 to 1,500 msec ($p < .01$).

Costs Plus Benefits

In this experiment, costs plus benefits—defined as invalid RT minus valid RT—reflect the combined cost of attending to an invalid frequency and the benefit of attending to a valid frequency. It may, therefore, be employed as a measure of the effect of the frequency cue on the distribution of attention (cf. Posner, 1978). Positive costs plus benefits (better performance on valid than on invalid trials) indicate that the cue engenders an allocation of attention to the cued frequency region. In contrast, neutral costs plus benefits (same level of performance on valid and on invalid trials) suggest that listeners use the cue only to alert themselves that a target is about to be presented.

Table 2
Percent Errors as a Function of Trial Type and Interstimulus Interval (ISI, in Milliseconds) in Experiment 2

Trial Type	ISI 500	ISI 1,000	ISI 1,500
Valid	3.94	3.09	2.86
Invalid–near	5.21	1.74	1.74
Invalid–far	5.56	4.86	3.47

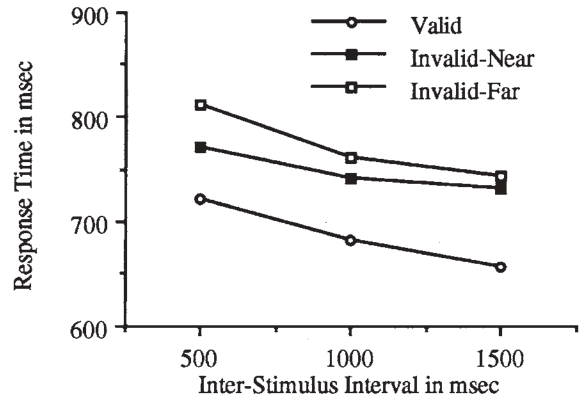

Figure 1. Response time as a function of trial type and interstimulus interval in Experiment 2.

Costs plus benefits were calculated for each condition and analyzed with a two-way ANOVA (frequency separation × ISI). Neither the main effects of frequency separation and of ISI nor the frequency × ISI interaction reached significance (all Fs < 1). However, duration judgments were made much more quickly when the target was preceded by a valid (687-msec) rather than by an invalid (760-msec) frequency cue [$t(11) = 3.59$, $p < .01$]. This effect, obtained for all 12 subjects, is of course consistent with an allocation of attention to the cued frequency region. Unlike a similar cue validity effect obtained in Experiment 1, this effect cannot be attributed to listeners' differential familiarity with the targets used, since all possible targets in Experiment 2 were presented equally often on valid and on invalid trials.

Discussion

The cue validity effect obtained in this experiment complements a similar effect apparent in Experiment 1 and provides strong evidence that attention is allocated in response to the frequency cue. Clearly, listeners may facilitate judgments about a specific feature of an auditory stimulus (duration) by orienting attention to the frequency at which that stimulus is presented.

A valid frequency cue may act both to draw attention to a specific frequency and to alert the subject that a target is about to be presented. In contrast, an invalid frequency cue may influence performance only by alerting listeners of a forthcoming target. Obviously, our data demonstrate that the frequency cue acts to draw attention to a specific frequency region since performance was substantially better on valid trials than on invalid trials. However, the equivalent improvement in performance for valid and invalid trials as a function of ISI suggests that this effect was mediated by the alerting properties of the cue. It appears, then, that attention may be fully engaged at a cued frequency region within 500 msec following a cue. This is perhaps unsurprising, given that Mondor and Zatorre (in press) have recently shown that an effect of cue validity on auditory target identification may be obtained within 100 msec following the onset of a spatial cue. In addition, many studies of visual spatial attention have also demonstrated such a fast developing cue validity effect (e.g., Mondor & Bryden, 1992; Remington & Pierce, 1983). The rather lengthy cue–target intervals used in this study (minimum of 500 msec) were chosen for two reasons. First, we wished to avoid the perceptual interactions between sequential sounds which are known to occur at brief ISIs (Bregman, 1990). Clearly such interactions would confound the interpretation of any obtained effect of the cue on target duration discrimination. Second, we wished to maintain the ISIs used in studies of frequency sensitivity in order to facilitate comparison of the results obtained in those studies with the results obtained from our own experiments. Our purpose is not to determine the speed with which attention may be allocated to a discrete frequency region, interesting though that issue might be in itself. Rather, we are at present only concerned with establishing that such an allocation is possible. More detailed analysis is warranted only once this basic capability has been established.

The results of Experiment 2 may also provide some insight into the characteristics of the focus of attention in response to a frequency cue. Two general classes of models have been proposed to describe the spatial focus of visual attention. Both types of models offer explanations of the effect of the cue observed in frequency sensitivity experiments. Spotlight models propose that attention may be allocated strictly to a discrete range of frequencies, centered at the frequency of the cue. According to this model, there is an even distribution of resources within the attended region and a fairly sharp demarcation between attended and unattended regions (Eriksen & Yeh, 1985; Posner, Snyder, & Davidson, 1980; Tsal, 1983). Alternatively, the attentional focus may be defined by a gradient with resources distributed across a rather large range of frequencies. According to this gradient model, the density of attentional resources is greatest at the cued frequency location and declines gradually with frequency separation from the focal point of attention (Andersen & Kramer, 1993; Downing & Pinker, 1985; Henderson & Macquistan, 1993; Shulman, Wilson, & Sheehy, 1985). Both spotlight and gradient models are consistent with the superior performance on valid trials as opposed to invalid trials obtained in Experiments 1 and 2. However, these two possible descriptions of the attentional focus are consistent with different effects of frequency separation on invalid trials. According to the spotlight model, the magnitude of the frequency separation between cue and target should not influence performance. Rather, equal performance should be obtained for all targets outside of the attentional beam. In contrast, a gradient model would be consistent with a consistent reduction in performance with increases in frequency separation between cue and target.

Because the effect of frequency separation on invalid trials failed to reach significance, the data of Experiment 2 are relatively more consistent with a spotlight of attention in which there is an abrupt distinction between attended and unattended frequencies. However, this result is not definitive. It is possible that attention is distributed as a gradient but that the invalid targets in this experiment were presented at sufficiently large frequency separations from the cue that few attentional resources were allocated to even the closest invalid target. Clearly, had this been the case, little further decrement in performance for targets at more extreme frequencies would be expected. The results obtained in Experiment 1, wherein a significant effect of frequency separation was obtained on invalid trials, provide some support for this possibility. These two experiments differed in the frequency separations employed on invalid trials, with much larger separations used in Experiment 2 than in Experiment 1. In fact, the smallest frequency separation in Experiment 2 was identical to the largest separation in Experiment 1. Clearly, then, the frequency separation used on invalid trials in Experiment 2 may have been too large to permit an adequate test of the nature of the attentional focus. The extent of the attentional focus was investigated again in Experiment 3, in which targets on some invalid trials were presented at smaller frequency separations from the cue than was the case in Experiment 2.

EXPERIMENT 3

In contrast to Experiment 2, three different frequency separations were used on invalid trials. While the widest of these frequency separations was identical to that employed in Experiment 2, the narrowest separation in Experiment 3 was much nearer to the frequency of the cue than was that in Experiment 2. We reasoned that this wider range of frequency separations on invalid trials would provide a more rigorous test of the possibility that the attentional focus may be described by a frequency gradient.

Experiment 3 differed from Experiment 2 in one other important respect. Recall that in each of the previous experiments the duration of the frequency cue was exactly midway between that of the short and long targets. This arrangement allowed the possibility that listeners used the cue as a standard or a "ruler" by which to compare or measure the duration of the target tones. If this was the case, then the cue validity effect might have occurred because the ease of comparison or measurement depended on the frequency similarity of the cue and the target tone. We attempted to reduce the possibility that listeners would adopt such a strategy by lengthening the frequency cue so that it was substantially longer than either of the possible targets and by varying cue duration randomly across trials.

Method

Subjects

Twelve undergraduate students attending McGill University were paid to participate in the experiment. All reported that their hearing was unimpaired. None of the subjects had participated in either Experiment 1 or Experiment 2.

Materials

Sounds. Short- (50-msec), and long- (100-msec) duration target tones were synthesized at fundamental frequencies of 667, 876, 1145, and 1500 Hz using the MITSYN software package (see Henke, 1990). These target frequencies, equally spaced on log-frequency coordinates, define the same frequency range as that used in Experiments 1 and 2. However, the frequency difference between adjacent targets was reduced from that employed in the previous experiments. Three different frequency cues, 150, 175, and 200 msec in duration, respectively, were also synthesized at each of the target fundamental frequencies. Both targets and cues were sine-wave tones with 5-msec linear onset/offset amplitude ramps. Sounds were presented at 65 dB SPL (C weighting) as measured by a GenRad sound level meter.

Computer system. The computer system was the same as that used in Experiment 1.

Design and Procedure

Experiment 3 differed from Experiment 2 in only a few respects. Cues and targets could be of any one of four different frequencies: 667, 876, 1145, and 1500 Hz. On invalid trials, three different frequency separations between cue and target were possible (invalid–near, invalid–medium, invalid–far). In addition, four different cue–target ISIs (500, 750, 1,000, and 1,500 msec) were used in order to examine more closely any changes in performance with opportunity to orient attention to a cued frequency position. The design of Experiment 3 was, in all other respects, identical to that of Experiment 2.

The subjects completed 96 practice trials and 768 experimental trials in each of two different sessions. They were provided with a brief break following the practice trials and again halfway through the experimental trials.

Results

The RT and error data are described in Figure 2 and Table 3, respectively.

Valid Trials

A one-way ANOVA (ISI) was conducted for both RT and errors. Analysis of the RT data revealed a significant main effect of ISI [$F(3,33) = 9.25$, $p < .001$]. Further analyses indicated that RT declined significantly as ISI increased from 500 to 750 msec ($p < .01$). This effect was complemented by a similar effect for the error data [$F(3,33) = 12.13$, $p < .001$]. Error rate declined significantly from the 750-msec to the 1,000-msec ISI and from the 1,000-msec to the 1,500-msec ISI ($p < .05$).

Invalid Trials

A two-way ANOVA (frequency separation × ISI) was performed for both RT and errors. For the RT data, only the main effect of frequency separation [$F(2,22) = 7.55$, $p < .01$] reached significance. Thus, performance for invalid–near trials exceeded that for invalid–far trials ($p < .01$), while performance for invalid–medium trials differed significantly only from that for invalid–far trials ($p < .05$). RT tended to decline as ISI increased [$F(3,33) = 2.58$, $p = .07$]. The frequency separation × ISI interaction did not reach statistical significance ($F < 1$).

For the error data, only the main effect of ISI reached significance [$F(3,33) = 3.23$, $p < .05$]. Thus, error rate declined as ISI increased from 500 to 1,500 msec. While the main effect of frequency separation did not reach significance [$F(2,22) = 1.67$, $p = .21$], error rate for targets presented close to the frequency cue (12%) tended to be lower than that for other targets (14%). The frequency separation × ISI interaction was not significant [$F(6,66) = 1.15$, $p = .34$].

Table 3
Percent Errors as a Function of Trial Type and Interstimulus Interval (ISI, in Milliseconds) in Experiment 3

	ISI			
Trial Type	500	750	1,000	1,500
Valid	16.37	14.49	12.47	10.02
Invalid–near	11.66	13.38	9.47	12.01
Invalid–medium	17.28	14.26	11.62	10.36
Invalid–far	18.19	11.66	11.71	12.91

Costs Plus Benefits

As discussed above, analysis of costs plus benefits provides an indication of the effect of cue validity on performance. Costs plus benefits for RT were significantly greater than zero [$t(11) = 5.40$, $p < .01$]. Thus, performance on valid trials (713 msec) exceeded performance on invalid trials (763 msec; the cue validity effect was apparent for 11 of 12 subjects). A two-way ANOVA (frequency separation × ISI) revealed a significant main effect of frequency separation [$F(2,22) = 7.55$, $p < .01$]. RT was significantly faster for invalid–near targets than for invalid–far targets ($p < .01$).

For error rate, costs plus benefits did not differ significantly from zero. A two-way ANOVA (frequency separation × ISI) indicated that neither the main effects of frequency separation [$F(2,2) = 3.24$, $p = .06$] and ISI ($F < 1$) nor the frequency separation × ISI interaction ($F < 1$) attained statistical significance.

Discussion

The results of Experiment 3 serve both to confirm and to extend those obtained in the previous two experiments. A strong effect of cue validity was again ob-

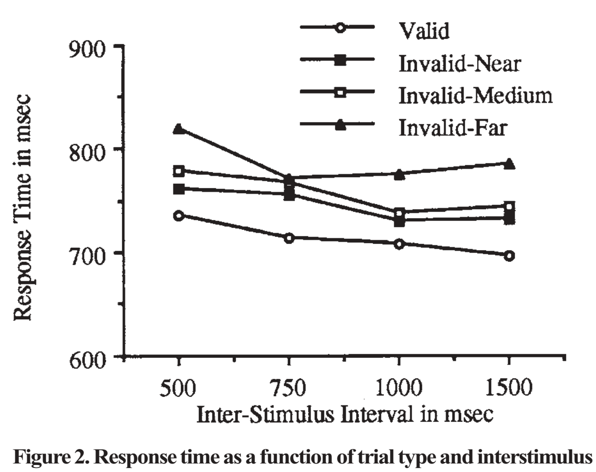

Figure 2. Response time as a function of trial type and interstimulus interval in Experiment 3.

tained, indicating that duration judgments may be made more quickly when targets are preceded by a valid rather than an invalid frequency cue. It is important to note that this effect was obtained even though the duration of the cue was lengthened to reduce the probability that listeners would use the cue as a ruler with which to measure the duration of the target.[3]

The significant effect of frequency separation is important in that it is consistent only with a gradient of attention wherein attentional resources decline with frequency separation from an attentional focal point (in this case, the focal point appears to be centered at the frequency of the cue). Any model that incorporates a sharp transition from attended to unattended regions is incapable of accounting for this result. It will be interesting to determine, in the future, whether the shape of the attentional gradient may be modulated by the attentional set and/or task demands imposed on the listener. Indeed, both Swets (1963) and Penner (1972) have argued persuasively that such cognitive factors play a critical role in frequency sensitivity experiments.

GENERAL DISCUSSION

In all three experiments, listeners were better able to judge the duration of a pure tone when it was preceded by a valid, rather than an invalid, frequency cue. This cue validity effect is important, because it establishes that listeners are able to allocate attention to a cued frequency region and, in so doing, to facilitate identification of a property of a sound that is independent of frequency (Allan & Kristofferson, 1974; Woods et al., 1979). The fact that this result was obtained with an identification task establishes that a detection paradigm is not necessary for demonstrating frequency sensitivity effects. In addition, relative to the detection paradigm, the identification paradigm appears likely to minimize effects of response bias because (1) all targets are presented well above threshold, (2) listeners are informed that tones of several different frequencies may be presented, and (3) all targets are equally likely to be preceded by a valid frequency cue as by an invalid frequency cue.

The significant effect of cue–target frequency separation in Experiments 1 and 3 strongly suggests that the focus of attention conforms to a gradient with the density of attentional resources declining with increasing frequency separation from the focal point of attention. As discussed above, such an effect is incompatible with the predictions of any model that incorporates a sharply defined attentional focus. An attentional gradient has also been shown to describe the spatial extent of the focus of attention in both audition (Mondor & Zatorre, in press), and vision (Andersen & Kramer, 1993; Downing & Pinker, 1985; Henderson & Macquistan, 1993; Shulman et al., 1985). Thus, a focus in the form of a gradient may be a general characteristic of the operation of attention for different representations of information and, indeed, for different sensory modalities.

It appears that visual spatial attention may be oriented by either of two different systems, which differ in the extent to which they rely on the conscious cooperation of the observer. Specifically, the exogenous system controls the automatic allocation of attention to sudden-onset visual events, whereas the endogenous system underlies the conscious allocation of attention to specific locations (Jonides, & Yantis, 1988; Müller & Rabbitt, 1989). The operation of these two systems is, then, typically associated with different types of attentional cues. The exogenous system is engaged by peripheral cues, such as a brief dot, the position of which signals the probable location of a forthcoming target. The endogenous system, on the other hand, is engaged by symbolic cues, such as an arrow, which must be interpreted before attention may be shifted to a specific location. Spence and Driver (in press) argued recently that exogenous and endogenous systems also operate in the covert orienting of auditory spatial attention. The frequency cue appears to be similar to a peripheral spatial cue in that it is a brief stimulus that is presented in close proximity to the probable frequency of a forthcoming target. Thus, the frequency sensitivity effect, as assessed in most studies, may reflect the operation of an exogenous attention system.

Support for the possibility that both exogenous and endogenous attention systems may operate in allocating attention to frequency regions may be derived from a recent study by Hafter, Schlauch, and Tang (1993). They examined the effect of two different types of cues on the frequency sensitivity effect. Listeners were cued as to the likely frequency of a target either by a standard cue of the type used in most previous studies or by a symbolic cue, the frequency of which was two thirds that of the target. Intriguingly, Hafter et al. discovered that the range of frequencies falling within a region of heightened sensitivity was larger when the symbolic cue, rather than the standard cue, was employed. This result suggests the possibility that the standard and symbolic cues each engage different attentional systems, and further, that the extent of the attentional focus depends on the system in operation. Thus, it appears likely that both endogenous and exogenous systems act to allocate attention to frequency regions, as well as to spatial locations (Henderson & Macquistan, 1992; Spence & Driver, in press).

While there may be similarities in covert orienting of attention in vision and audition, there may also be differences between these systems. Schlauch and Hafter (1991) reported that listeners could improve detection of a tone with a frequency identical to that of any of several frequency components of a complex cue. Performance declined as the frequency separation between the tone target and the frequency components of the cue increased. The authors argued that detection of tones of expected and unexpected frequencies may be accounted for by a model in which the listener monitors several auditory filters simultaneously. If this effect can be shown to result from the simultaneous allocation of attention to several different frequency regions, such an ability may stand in contrast to that apparent in vision, where observers are evidently unable to attend to more than one location at a time (e.g., Eriksen & Webb, 1989). This potential differentiation may provide evidence that distinct attentional mechanisms operate on some types of auditory and visual information. Such a differentiation would not be surprising, given that sound frequency is represented at cortical and subcortical structures that are quite distinct from those involved in visual information processing (Aitkin, 1986, 1990; Altschuler, Bobbin, Clopton, & Hoffman, 1991; Gulick, Gescheider, & Frisina, 1989).

Finally, our demonstration that attention may be selectively allocated to a specific frequency region may have implications for the role of attention in auditory scene analysis in general and in auditory stream segregation in particular. *Auditory stream segregation* refers to a perceptual phenomenon in which a repeating sequence of high and low tones is heard, at high rates, to segregate into two different streams, one composed of the high tones and the other of the low tones. Specifically, the repetition rate at which the stream segregates is inversely related to the frequency separation between the high and low tones. Jones (1976) has argued that the integration of tones into a single stream is accomplished through an attentional mechanism. Jones's theory depends on a quite complex process in which an algorithm descriptive of a particular tone sequence is first established and attention is then allocated selectively on the basis of the extracted algorithm. The rate with which attention can be shifted between two frequencies is, however, limited. Thus, segregation is proposed to occur when attention is no longer able to shift between successive tones of a sequence. The data reported in this paper demonstrate that attention may be oriented to a specific frequency region 500 msec following a cue. However, an integrated percept of a tone sequence is often maintained at rates of less than 100 msec between tones. In spite of the heavy emphasis of Jones's theory on the deployment of attention, it is uncertain whether attention may be shifted selectively within 100 msec in accordance with a computed algorithm descriptive of a tone sequence. However, the paradigm developed in this paper may clearly be of considerable use in addressing this issue.

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NOTES

1. All post hoc tests in the remainder of the paper were performed using the Tukey HSD procedure.

2. The constraint that listeners be equally familiar with all targets used in the experiment meant that invalid–far trials could occur only following a cue to one extreme and a target to the opposite extreme frequency (for example, a cue of 667 Hz and a target of 1500 Hz). This arrangement could influence the outcome of the experiment only if cues of certain frequencies were more effective than cues of other frequencies. There is no evidence to support this possibility since, as noted above, duration has been shown to be independent of frequency (Allan & Kristofferson, 1974).

3. Were subjects using the cue as a ruler, better performance might have been expected for the shortest cues, which were most similar in duration (150 msec) to the longest target tone. A post hoc analysis of performance on valid trials revealed no significant effect of the duration of the frequency cue on target identification ($F < 1$).

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