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The role of auditory memory traces in attention to frequency

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Three cued signal detection experiments demonstrated a role for auditory memory traces in frequency selectivity. The extent to which the cue predicted the signal frequency affected the size of the advantage for signals at the cue frequency over those at distant frequencies when the cue–signal gap was 10 sec but not when it was 1 sec. Detection of occasional signals presented at uncued frequencies was enhanced when they matched the frequency of cues from recent trials. With "relative" cues, which were usually followed by signals at the musical fifth above the cue frequency, performance on occasional signals at the cue frequency was enhanced relative to other unexpected frequencies. These results suggest that, regardless of the listener's expectations and intentions, the detectability of a signal is enhanced if its frequency matches an existing memory trace. One form of voluntary attention to frequency may involve maintaining traces that would otherwise slowly decay.

Psychophysical studies of auditory attention have established that listeners' ability to detect a signal is better when the frequency of the signal is predictable than when it is unexpected or uncertain from trial to trial (e.g., Greenberg, 1969; Greenberg & Larkin, 1968; Penner, 1972). Much research into selective frequency listening has employed variations of Greenberg and Larkin's (1968) probe-signal procedure, in which an expectation that the signal will be at a particular frequency is typically set up by preceding each trial with a clearly audible cue tone at that frequency. While performance on expected (cued) frequencies is high, detection of infrequently presented signals (probes) at unexpected frequencies declines to much lower levels as the difference from the expected frequency increases. The pattern of detection performance across frequencies is commonly referred to as the *probe-signal contour* and may be regarded as representing an attention (or listening) band—that is, a frequency region in which auditory processing is enhanced (Botte, 1995; Dai & Buus, 1991; Dai, Scharf, & Buus, 1991; Scharf, Quigley, Aoki, Peachey, & Reeves, 1987).

The advantage for expected signal frequencies has been interpreted as resulting from voluntary attentional processes reflecting the listener's intention to focus at particular frequency regions. Considerable initial evidence suggested that the probe-signal contour was determined by a property of cochlear filtering, termed *the critical band*, at the signal frequency (Hafter, Schlauch, & Tang, 1993; Hübner & Hafter, 1995; Leek, Brown, & Dorman, 1991; Schlauch & Hafter, 1991). On this basis, one interpretation was that listeners monitored the output of only the auditory filter centered at the expected frequency. However, by obtaining from the same participants both probe-signal contours and estimates of auditory filter shape, Moore, Hafter, and Glasberg (1996) demonstrated that the probe-signal contour does not result solely from peripheral filtering. They proposed that detection was governed by the degree of match between the representation of the current stimulus and a voluntarily maintained template consisting of a stored description of the expected signal. The concept of selection resulting from a voluntarily controlled template-matching process has been proposed in several theories covering various aspects of attention, such as Duncan and Humphreys's (1989) account of visual search performance and models of the signal processing involved in the detection of tones in noise (Dau, Püschel, & Kohlrausch, 1996).

Importantly, however, subsequent evidence has demonstrated that attention to frequency, like both auditory and visual spatial attention, is controlled not only by voluntary processes that reflect listeners' expectations and intentions, but also by involuntary processes that can be triggered by the mere presentation of stimuli, regardless of the observer's intentions (e.g., Justus & List, 2005; Mondor & Breau, 1999; Mondor, Breau, & Milliken, 1998; Mondor, Hurlburt, & Gammell, 2003; Mondor, Zatorre, & Terrio, 1998; Prime & Ward, 2002; Ward, 1997). This evidence comes largely, though not exclusively, from stud-

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ies that have contrasted what are termed *informative* and *uninformative* frequency cues. Of course, to some extent, any sound can be regarded as providing information. In this context, however, informativeness is defined in terms of the extent to which the frequency of the cue predicts that of the subsequent signal. Cues are regarded as informative when there is a high probability that the signal will be at the frequency indicated by the cue. In contrast, uninformative cues are no more likely to indicate the target frequency than they are a different frequency, and participants are instructed to ignore them. On the basis that such cues do not enable prediction of the frequency of the target, better performance on targets that match the cue frequency is interpreted as evidence of involuntary attention.

Mondor and colleagues have suggested that evidence of involuntary attention to task-irrelevant frequency cues can be accommodated within a template account of auditory attention. They proposed that when the listener is unable to set the template in advance because the nature of the target is unpredictable, the parameters of the template may be set in a bottom-up manner by the features of the cue on a given trial. Typically, studies of involuntary attention to frequency have analyzed measurements of reaction time (RT) obtained in tasks using suprathreshold stimuli. Some caution is necessary in relating such evidence to performance in signal detection tasks, since the nature of the effects obtained in studies of attention may depend to a considerable extent on the precise details of the experimental paradigm used. For example, Prime and Ward (2002) provided evidence suggesting that in RT experiments, the facilitatory effects of a cue matching the frequency of the target could be counteracted by a form of response inhibition. The need to withhold a response to the cue stimulus may lead to a carryover effect of slowed responding to the subsequent target. In addition, there is evidence from studies of visual spatial attention that RT and accuracy measures may reflect different aspects of underlying processing (Handy, Kingstone, & Mangun, 1996; Prinzmetal, McCool, & Park, 2005).

However, one previous study has provided evidence of involuntary attention to frequency in cued signal detection tasks: In a series of experiments conducted by Green and McKeown (2001), detection performance with uninformative cues was consistently better on the occasional trials when the target matched the frequency of the cue (valid trials) than on the remaining trials when it was at one or other distant frequency (invalid trials). One finding arose from direct comparisons of performance with uninformative versus informative cues. Fitting probe-signal contours with a model of the auditory filter (Patterson & Moore, 1986) showed that attention bands were wider by a factor of about 1.2 when cues were informative. A second finding was that the facilitatory effects of uninformative frequency cues were apparent with intervals between cue and target of as long as 3 sec. This is much longer than the duration of the facilitatory effects of uninformative frequency cues found in the experiments of Mondor and colleagues, and of the involuntary effects typically reported in studies of spatial attention in both vision and audition.

Green and McKeown (2001) suggested that the involuntary effects of cues on detection performance could be explained in terms of the influence of memory traces of previously presented stimuli. Cowan (1984) identified two phases of auditory sensory memory: a brief afterimage lasting a few hundred milliseconds, and a more processed memory preserving sensory features for up to 10 sec or more, corresponding closely to what has been termed *synthesized auditory memory* (Massaro, 1975). Much evidence regarding the properties of auditory stimulus representations in this more enduring form of sensory memory has been gained from studies of the effects of preceding sounds on the event-related potentials (ERPs) elicited by auditory stimuli (for reviews, see Näätänen & Winkler, 1999; Schröger, 1997; Winkler & Cowan, 2005). In the context of cued detection tasks, among the important properties of these memory traces are: (1) They are formed and stored largely automatically, with little influence of ongoing voluntary operations; (2) the traces of several recent stimuli can exist simultaneously; and (3) traces decay gradually over a period of several seconds, unless reinforced by a recurrence of the same stimulus, or maintained by a voluntary process. Drawing on such evidence, Green and McKeown (2001) suggested that, independent of listeners' intentions, detection of a particular signal is enhanced when the sensory memory system contains a trace of a previous stimulus at the same frequency.

The current study contains three experiments that further explore the possible role of memory traces in mediating the effects of frequency cues on signal detection performance. The first examines the effects of very long delays between cue and signal. The second investigates whether the probability of detecting a signal may be influenced not just by the cue on that particular trial, but also by the slowly decaying memory traces of cues on previous trials. The third assesses possible involuntary effects of cues that create an expectation that the signal will be at a fixed ratio of the cue frequency.

EXPERIMENT 1

Green and McKeown (2001) suggested that the voluntary attentional processes invoked in response to an informative cue may involve rehearsal of the memory trace of the cue; that is, whereas the traces of uninformative cues slowly decay, in the case of informative cues, a voluntary rehearsal process may serve to maintain the strength of the trace, thereby aiding detection of signals at the cue frequency. With a delay between cue offset and the first observation interval of 1 sec, Green and McKeown (2001) found that the advantage for valid trials over invalid trials was only slightly greater with informative than with uninformative cues. This might reflect the fact that, with only a 1-sec delay between cue and target, there is relatively little decay of the memory trace of uninformative cues, so that the posited voluntary maintenance of the trace when cues are informative can only have a small effect.

In the present experiment, a comparison between performance with informative and uninformative cues is made with a delay between cue and first observation interval of either 1 sec or 10 sec. With the longer delay, it is expected that the trace of uninformative cues will have decayed substantially before the signal appears, but when cues are informative the trace will have been voluntarily maintained. On the assumption that this process will aid detection of signals matching the frequency of the maintained trace, it is predicted that the effect of whether cues are informative or uninformative on the advantage for valid over invalid trials will be larger when the delay is 10 sec than when it is 1 sec.

Method

Participants. The four listeners each had normal hearing and some experience in auditory signal detection tasks. One (S4) was the first author.

Stimuli and Equipment. Tones were generated on a DigiDesign Audiomedia II DSP soundcard installed in a Macintosh Quadra 650 computer, synthesized in real time using custom software at a sampling rate of 44.1 kHz, and output through the soundcard's 16-bit digital-to-analog converters. All tones were of 250-msec duration, including 15-msec cosine rise and fall times. Background white noise at a spectrum level of 35 dB SPL (Brüel & Kjaer WB 1314 noise generator) was present continuously. Stimuli and noise were separately attenuated (Tucker Davis Technologies PA4), mixed (Tucker Davis Technologies SM3), and bandpass filtered (Kemo VBF21M, 100 Hz to 6 kHz, 24 dB/octave). Participants listened through the right earpiece of Sennheiser HD580 headphones while seated in an Industrial Acoustics Company double-walled A-series soundproof chamber. The experiment was controlled from the Macintosh computer. Cues and signals were drawn from a set of 12 frequencies, equally spaced on a logarithmic scale between 0.67 and 5.00 kHz.

Threshold measurements. Listeners' thresholds for tones in the noise masker had previously been measured at a minimum of eight frequencies within the range 0.5–5.0 kHz, using an adaptive two-alternative forced choice (2AFC) one-up two-down procedure (Levitt, 1971). The initial step size of 3 dB was reduced to 0.5 dB after the seventh reversal and the threshold for a run was based on the mean of eight reversals at the 0.5-dB step size. Thresholds were calculated from the average of at least two such runs. Some signals were presented at frequencies at which thresholds had not been measured directly. Since thresholds in noise increase approximately linearly with frequency (D. M. Green, McKey, & Licklider, 1959), a regression line was fitted to the thresholds obtained for each listener and used to estimate thresholds in these cases.

Design and Procedure. A 2AFC task was used. The two observation intervals were separated by 350 msec and were equally likely to contain the signal. Participants initiated each trial and responded using a response box that marked the observation intervals with lights and provided visual feedback after each response. The time delay between cue-offset and the first observation interval was either 1 sec or 10 sec. For both delays, there were separate conditions in which cues were informative (75% valid) or uninformative (25% valid). Trials were presented in blocks of 48, with each frequency presented as the cue on four occasions. Invalidly cued signals following a given cue frequency were presented at 9 of the 11 other frequencies, with the frequencies immediately above and below the cue frequency excluded.[1] The minimum frequency ratio between an invalidly cued signal and the cue was 1.44. In informative cue conditions, each different cue frequency was followed by an invalidly cued signal only once within a block, so that nine different blocks were necessary to incorporate all the combinations used, whereas the uninformative cue condition required three different blocks.

For each delay (1 and 10 sec), a no-cue condition was included in order to check that the twelve frequencies were approximately equally detectable.[2] The 1-sec no-cue conditions were completed first, with signals initially presented at 2 dB above threshold. In some cases, levels were adjusted in order to ensure approximately equal detection across each frequency and an overall level of performance of around 65%–70% correct. In the majority of cases, levels remained at 2 dB above threshold; where levels were adjusted they fell within the range 1–4 dB above the estimated thresholds. Signals in the main experimental conditions were presented at these levels; cues were presented 8 dB higher. In the main experiment, two listeners performed the cued 10-sec delay condition, followed by the cued 1-sec delay condition. The reverse was true for the other two listeners. In each case, the order of informative and uninformative cue conditions was counterbalanced. Informative cue conditions were always preceded by blocks of trials, with 100% valid cues in order to encourage listeners to focus at the frequency of informative cues. Conversely, uninformative cue conditions were always preceded by blocks of trials with 0% valid cues, to discourage intentional focusing at the cue frequency.

Participants completed a total of 432 trials in all conditions except the no-cue, 0%, and 100% conditions with the 10-sec delay, in which only 108 trials were completed in order to minimize time requirements. Listeners were always informed of the percentage of valid cues, and were accordingly instructed to either attempt to focus at the frequency of the cue, or to attempt to ignore its frequency. In addition, they were made aware that when signals were not at the cued frequency, they could appear at any of a wide range of possible frequencies.

Results and Discussion

With the 1-sec delay, performance on validly cued trials was substantially better than that on invalidly cued trials, both when cues were informative and when they were uninformative (Figure 1). The mean advantage for valid over invalid trials was similar in both cases, being 16.2% with informative cues and 12.3% with uninformative cues. There was, however, substantial variation in the size of the advantage for valid trials across listeners. With informative cues the range was 3.4%–24.0%, whereas with uninformative cues it was 4.6%–17.9%. For completeness, Figure 1 also shows performance in the no-cue, 0%, and 100% conditions, which preceded the main experimental blocks.

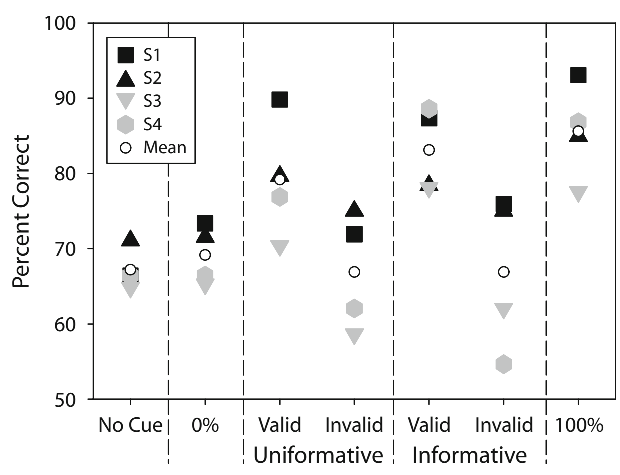

Figure 1. Performance on valid and invalid trials in uninformative (25% validity) and informative (75% validity) cuing conditions with a 1-sec delay in Experiment 1. Also shown is performance in no-cue, 0% validity, and 100% validity conditions.

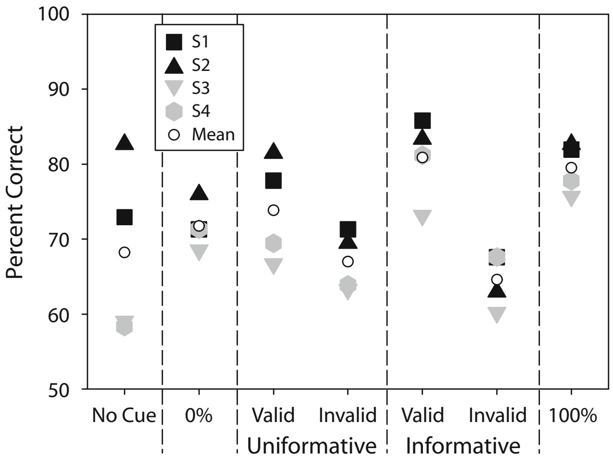

Figure 2. Performance on valid and invalid trials in uninformative (25% validity) and informative (75% validity) cuing conditions with a 10-sec delay in Experiment 1. Also shown is performance in no-cue, 0% validity, and 100% validity conditions.

As shown in Figure 2, with the 10-sec delay the mean advantage for validly cued over invalidly cued trials was substantially larger when cues were informative (16.3%) than when they were uninformative (6.9%). There was less variability across listeners than was apparent with the 1-sec delay, with the advantage for valid over invalid trials ranging between 13.0% and 20.5% with informative cues and between 3.4% and 12.04% with uninformative cues. The difference in the advantage for valid trials was largely due to considerably higher performance on valid trials when cues were informative rather than uninformative.

Percent correct detection scores were submitted to a repeated measures ANOVA with factors of trial type (valid or invalid), proportion of valid cues (i.e., whether cues were informative or uninformative), and delay. There was a significant effect of trial type [$F(1,3) = 70.80$, $p = .004$], no significant effect of the proportion of valid cues [$F(1,3) = 2.34$, $p = .223$], and no significant effect of delay [$F(1,3) = 4.20$, $p = .133$]. The two-way interaction between trial type and proportion of valid cues was not significant [$F = 7.22$, $p = .075$]; nor were the two other two-way interactions (Fs < 1). Although the mean advantage for validly cued trials over invalidly cued trials is similar for informative and uninformative cues in the short delay condition but substantially larger for informative cues in the long delay condition, the three-way interaction between trial type, proportion of valid cues and delay was not significant ($F < 1$). This is contrary to the expectation that the size of the advantage for valid relative to invalid trials would be affected by the proportion of valid cues when the delay was long but not when it was short. However, it is noticeable that there was considerably larger variability in performance in the short-delay condition than in the long-delay one. Why variability varied across delay in this way is unclear, but this variation could account for the absence of the expected significant three-way interaction. In order to further examine the influence of the proportion of valid trials on performance at each delay, separate two-way ANOVAs with factors of trial type and proportion of valid cues were carried out for each delay condition.

With the 1-sec delay, there was a significant main effect of trial type [$F(1,3) = 11.71$, $p = .042$], no significant main effect of proportion of valid trials [$F(1,3) = 2.22$, $p = .233$], and no significant interaction [$F(1,3) < 1$]. With the 10-sec delay, the main effect of trial type was significant [$F(1,3) = 42.79$, $p = .007$], but there was no significant effect of proportion of valid cues [$F(1,3) = 1.26$, $p = .343$]. Importantly, in contrast to the 1-sec delay case, the interaction between trial type and proportion of valid cues was significant when the delay was 10 sec [$F(1,3) = 125.91$, $p = .002$].

If the absence of a significant three-way interaction in the initial analysis was attributable to the substantial variability across listeners apparent in the 1-sec delay condition, it must be acknowledged that this variability might also mask an interaction between trial type and proportion of valid cues in the 1-sec delay condition; some caution is warranted, therefore. Note, however, that in the comparison between informative and uninformative cue conditions performed in Green and McKeown (2001)—in which the delay was also 1 sec and there was much less variation across listeners—there was no significant interaction between trial type and proportion of valid cues either. There is, therefore, some support here for the proposal that detection performance is mediated by the sensory memory trace of the cue, which slowly decays when cues are uninformative, but is voluntarily maintained when listeners know that the signal is likely to appear at the cue frequency.

It is interesting to note that there is some previous evidence to suggest that voluntary rehearsal of the frequency of a tone over a silent delay of several seconds does not aid performance in a frequency discrimination task (Keller & Cowan, 1994; see also Demany, Montandon, & Semal, 2004). Green and McKeown (2001) suggested that their finding of wider attention bands for informative rather than uninformative cues might arise from a rehearsal process that, while maintaining the strength of the memory trace, serves to blur the representation of accurate frequency information, due to the operation of positive feedback loops between different cortical areas. While speculative, such an account would appear to reconcile the apparently different effects of voluntary rehearsal of a tone's memory trace on signal detection and frequency discrimination.

It should also be acknowledged that the assumptions underlying the application of the cuing paradigm here—that is, that listeners attempt to heighten sensitivity at the cue frequency when cues are informative while attempting to remain equally sensitive across the frequency range when cues are uninformative—may be open to question. There are a number of plausible ways in which listeners' strategies may depart from these assumptions. For example, listeners might focus at the cue frequency on some trials within a block and not on others, depending perhaps both on the overall proportion of valid cues and their experience of the most recent few trials. In uninformative cue conditions, they may reason that a low-frequency cue is likely to be followed by a signal at a higher frequency, and therefore attempt to enhance sensitivity in high-frequency regions and vice versa.

Such considerations emphasize the need for caution in interpreting performance based on assumptions regarding listeners' strategies. The subsequent experiments focus on identifying evidence for involuntary attention to the frequency of previously presented sounds in contexts in which concerns regarding such questions are minimized.

EXPERIMENT 2

Green and McKeown (2001) observed that the advantage for signals at the cue frequency over those distant in frequency from the cue appeared to be influenced by the number of different frequencies presented within a block of trials. One experiment compared the effects of informative and uninformative cues using just four widely spaced possible frequencies. Even with informative cues, the enhancement in detection performance for validly cued trials over invalidly cued trials was substantially smaller than in other experiments that used only uninformative cues but that had 9 or 12 possible frequencies. This difference in cuing effects could reflect a difference in listening strategy. It is conceivable that, regardless of the informativeness of the cue, with only a small number of possible frequencies listeners may at least to some extent have attempted to monitor all four frequencies, which, as previous evidence suggests, could be achieved fairly successfully (Macmillan & Schwartz, 1975; Schlauch & Hafter, 1991). Thus, on this account the relatively small advantage for valid trials over invalid trials is because of voluntary attention to the frequencies of signals on invalid trials.

However, Green and McKeown (2001) suggested an alternative explanation on the basis of involuntary effects. The time interval between presentation of signals in their experiments was typically around 3–4 sec. Both behavioral and ERP evidence indicates that sensory memory traces can take 10 sec or longer to decay (Böttcher-Gandor & Ullsperger, 1992; Cowan, 1984; Sams, Hari, Rif, & Knuutila, 1993). Therefore, with only a small number of possible frequencies, there is a relatively high probability that invalidly cued signals were presented at frequencies for which a trace of a cue from a previous trial was still present in sensory memory. If the probability of detection of a signal is increased if it matches an existing sensory trace, this could result in increased performance on invalid trials and therefore explain the smaller cuing effects found with a smaller number of possible signals.

In Experiment 2, this possibility is directly investigated by comparing performance on two types of invalidly cued trial, those in which the signal is presented at the same frequency as the cue from the immediately preceding trial, and those in which the signal is at a frequency not presented for at least the four previous trials. Better performance in the former case would support the hypothesized influence of the slowly decaying sensory memory traces of cues from previous trials.

Method

Participants. The four listeners included three who took part in Experiment 1 and one new to signal detection tasks.

Design and Procedure. Cues and signals were drawn from the same set of 12 frequencies used in Experiment 1. Except where stated below, other aspects of the Method were the same as those in Experiment 1. The interval between cue offset and the first observation interval was 1 sec. Trials were presented in blocks in which each frequency appeared four times as cue and four times as signal. There were 36 valid trials within each block, 3 at each of the 12 possible frequencies. The remaining 12 invalid trials each had a different cue frequency. Invalidly cued signals following a given cue frequency were always at one particular frequency. The choice of these pairings was largely arbitrary, with the constraint that there was a large frequency separation, well beyond a critical band, between cue and signal.

Each block contained six invalidly cued trials on which the signal was at the frequency of the cue from the previous trial (*trace trials*), and six on which the signal was at a frequency which had not appeared in at least the four previous trials (*no-trace trials*). The duration of each trial from cue onset to the end of the second observation interval was 2.1 sec. Measurements of the time taken to complete blocks showed that the mean time taken up by listeners' responses and the starting of the next trial was approximately 1.9 sec. On this basis, signals on trace trials were presented, on average, 5.55 sec after the onset of the cue from the previous trial, while signals on no-trace trials were presented at least 21.55 sec after the previous presentation of a cue at the same frequency.

To ensure that the comparison between trace and no-trace trials was not affected by differences in the inherent detectability of individual frequencies, two different trial orders were created. The frequencies at which signals were presented on the six trace trials in the first order were used for the six no-trace trials in the second order, and vice versa. Each listener completed 32 blocks, 16 of each of the different trial orders. They were told that the signal would be at the same frequency as the cue on 75% of trials so that focusing at the cue frequency would be advantageous.

Results and Discussion

As shown in Figure 3, mean performance on valid trials was at a high level. Mean performance on trace trials was approximately 6% better than that on no-trace trials, though

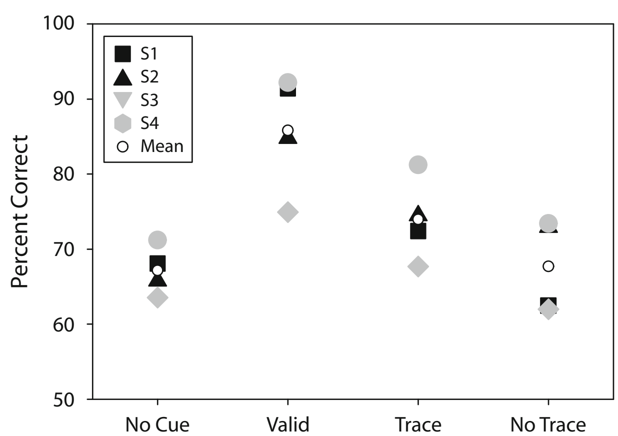

Figure 3. Performance in Experiment 2 for valid trials, and two types of invalid trial: *trace*, in which the signal was at the frequency of the cue from the previous trial; and *no-trace*, in which the signal was at a frequency that had not been presented for several trials. Performance in the no-cue condition is also shown.

still around 12% lower than that on valid trials. The pattern of results was largely similar across the four listeners. In all cases performance was highest on valid trials, lowest on no-trace trials, and at an intermediate level on trace trials. A two-tailed repeated measures *t* test showed that the difference in performance on trace and no-trace trials was significant [$t(3) = 3.51, p = .039$].

Because cues were informative in the present experiment, listeners may have intentionally focused at the cue frequency; the high performance on valid trials probably therefore involved voluntary processes. Although, as previously acknowledged, there can be no certainty regarding the strategies actually adopted, it does not seem plausible that listeners would have intentionally focused at the frequency of the cue from the previous trial.[3] Thus, the higher performance on trace than on no-trace trials represents an involuntary effect of the cue from the previous trial and is consistent with the interpretation that involuntary cuing effects are mediated by auditory memory traces.

EXPERIMENT 3

The results of the previous experiments suggest that in the typical cued detection task, in which valid cues are followed by a signal at the same frequency as the cue, the better performance obtained on valid than on invalid trials can be interpreted in terms of an advantage for signals that match the memory trace of the cue, which slowly decays when cues are uninformative but is voluntarily maintained when they are informative. However, voluntary processes in selective frequency listening cannot be restricted to this voluntary maintenance of the memory trace of the cue. This is demonstrated by evidence that listeners are able to make use of what are termed *relative cues*, which, when valid, are followed by a signal at some fixed ratio of the cue frequency (Hafter et al., 1993; Hübner & Hafter, 1995).

Hafter et al. (1993) compared performance using relative cues with performance in the typical case in which valid cues precede signals at the same frequency as the cue, which they termed *iconic* cuing. Performance on valid trials in the relative cuing condition was high (around 80%–90%), although slightly lower than that on valid trials in the iconic cuing condition; attention bands were wider by a factor of approximately 1.6 with relative than with iconic cues. In addition to the occasional probe signals presented at various ratios of the expected frequency used to determine the probe-signal contour, on a very small proportion of trials in the relative cuing condition (approximately 1 in 30) the signal was presented at the cue frequency. Performance on these trials was poor, being very similar to that at the most distant probe frequencies. This was regarded as evidence that listeners were not voluntarily monitoring the cue frequency. In accord with this, Hübner and Hafter (1995) reported that psychometric functions obtained in both iconic and relative cuing conditions were consistent with models that assumed that listeners monitored a single frequency band—albeit with a wider bandwidth for relative cues.

However, the poor performance observed by Hafter et al. (1993) on signals at the cue frequency, when signals are more likely to appear at other frequencies, is in contrast to the evidence of involuntary effects of frequency cues reported here and in Green and McKeown (2001). As noted above, when cues are relative and attention must be focused at a frequency far from that of the cue, it is likely that the attentional processes involved are somewhat different to those operating in our previous experiments. It is possible that in some way this eliminates the effects of the memory trace of the cue on detection performance.

It is also possible, though, that given the rarity of trials in which the signal was presented at the cue frequency in Hafter et al.'s (1993) relative cue condition, the low rate of detection of these signals might be explained in terms of the "heard but not heeded" account described by Scharf et al. (1987); that is, listeners may have detected signals at the cue frequency but not identified them as signals.

Here, performance on signals presented at the same frequency as a relative cue is examined when such signals occur on one of every eight trials. As in Hafter et al.'s (1993) relative cue condition, signals appear at the musical fifth above the cue frequency on 75% of trials, so listeners are assumed to focus at that frequency. On the remaining trials, the signal is equally likely to appear at the cue frequency or at another frequency far removed from both the cue frequency and the expected frequency. If the memory trace of the cue does provide an advantage for detection of signals at the cue frequency, even when attention is voluntarily shifted to another frequency, performance for signals at the cue frequency could be expected to be significantly better than that for signals that are at neither the cue nor the expected frequency.

Method

Participants. The four listeners, including the first author (S4), had all participated in at least one of the previous experiments.

Procedure. The interval between cue offset and the first observation interval was 1 sec. Cues were presented at four logarithmically spaced frequencies: 0.5, 0.9, 1.62, and 2.92 kHz. Signals could be presented at these four frequencies and also at values corresponding to the musical fifth above each cue frequency: 0.75, 1.35, 2.43, and 4.37 kHz (subsequently referred to as relative target frequencies). The number of possible cue frequencies was restricted to four so that the relative target frequencies never occurred in the same critical band as any of the possible cue frequencies. Thus, the detection of relatively cued signals should not be affected by the decaying memory traces of cues on previous trials.

Listeners first completed three no-cue conditions: In the first (no-cue A), signals were presented with equal probability at each of the eight frequencies; in the second (no-cue B), signals were only presented at the relative target frequencies; in the third (no-cue C), the proportions of signals at each frequency were identical to those in the main relative cue condition. These conditions allowed a check on whether signals at cue frequencies were inherently more detectable than those at relative target frequencies, and whether performance in no-cue conditions varied according to inequalities in the probability of presentation of signals at different frequencies. Sixteen blocks of 48 trials were completed in the no-cue A and C conditions and 10 blocks of 48 trials in the no-cue B condition.

Listeners then completed a 100% valid relative cuing condition. Initial practice blocks were completed with a reduced level of background noise. When the noise was restored to its normal level, performance quickly reached high levels after just a few blocks for all listeners. Once performance had reached stable levels, a further 15 blocks (720 trials in total) with 100% valid relative cues were completed.

In the main relative cuing condition the cue was valid on 75% of trials. Invalid trials were equally divided between those in which the signal was presented at the cue frequency (*cue-f trials*), and those in which the signal was presented at one of the other three relative target frequencies (*other-f trials*). Using relative target frequencies in other-f trials acted as a check on the possibility that listeners might adopt a strategy of listening at the four relative target frequencies rather than just the single target indicated on each trial. Such a strategy might result in good performance on valid trials, but would also be expected to result in high performance levels on other-f trials. Overall, cue-f trials were equally likely to be at any of the four cue frequencies and other-f trials were equally distributed over each of the 12 possible combinations (4 cue frequencies × 3 signal frequencies). Twenty blocks of 48 trials were completed.

The author, of course, had exact knowledge of the probability of the various types of trial within a block. The other listeners were made aware of the high proportion of valid trials within a block and were instructed to attempt to focus on the likely frequency of the signal on each trial. They were given no information regarding the frequencies at which invalidly cued signals would appear.

Results and Discussion

Performance was very similar in all three no-cue conditions. All four listeners showed slightly better performance on relative target frequencies than on cue frequencies in the experimental probability condition (no-cue C); thus, cue frequencies were clearly not inherently more detectable than relative target frequencies. Mean performance in each no-cue condition was within the 68%–70% range, so that the variation in the probabilities with which the two sets of frequencies were presented had little effect on performance.

As shown in Figure 4, in the main relative cuing condition mean performance on cue-f trials was around 15% lower than that on valid trials, but was over 12% higher than that on other-f trials. The poor performance on other-f trials suggests that listeners did not monitor on each trial the four possible relative target frequencies. Because performance on valid trials in the main relative cue condition was virtually identical to that in the 100% valid condition, and because performance on cue-f trials was substantially lower than that on valid trials, it seems highly unlikely that listeners were voluntarily attending to both the expected relative target frequency and the cue frequency.

A repeated measures t test showed that the difference between performance on the two types of invalidly cued trial, cue-f and other-f, was significant [$t(3) = 3.34$, $p = .044$]. Because the results of the author—who knew which frequencies would be presented—showed the largest difference between performance on these two types of trial, further analysis was performed with the author's data excluded. Data was collapsed across the remaining three listeners to provide a single proportion correct for cue-f and other-f trials. The difference between these proportions was then assessed following the procedure described by Macmillan and Creelman (1991, p. 269) and was found to be significant [$z = 2.570$, $p = .010$].

This better performance on cue-f relative to other-f trials is in contrast to Hafter et al.'s (1993) finding of poor performance on signals at the cue frequency. One factor underlying this difference may be the higher proportion of trials in which the signal appeared at the cue frequency

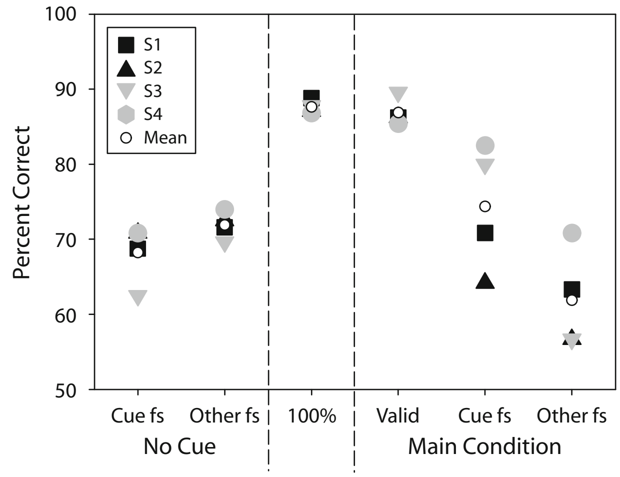

Figure 4. Performance in Experiment 3 for valid trials (signal presented at the musical 5th above the cue frequency) and two types of invalid trial: *cue-f* (signal at cue frequency), and *other-f* (signal at a frequency that would have been presented on a valid trial for a different cue frequency). For comparison, also shown are performance in the 100% condition, and in no-cue condition C, in which signals appeared at each frequency with the same probability as in the main relative cuing condition.

in the present case, which may have reduced any tendency for listeners to regard perceived signals at the cue frequency as nonsignals.

A further difference between the experiments that might be relevant is that there were only four possible relative target frequencies in the current study, whereas in Hafter et al.'s (1993) study the expected frequency varied randomly from trial to trial over a wide range. The voluntary process involved in shifting attention to the appropriate expected frequency may differ in some way, with the consequence that involuntary effects on sensitivity at the cue frequency are apparent with a small number of possible frequencies, as in the current case, but not when frequencies are selected at random as in Hafter et al. (1993). Some evidence that supports this notion is provided by extra conditions carried out with the author as the sole listener.

Attention bands were measured using the method described in Green and McKeown (2001) with both relative and iconic cues when the number of cue frequencies was either four or eight. Performance on validly cued trials was close to 90% in each case. With eight possible cue frequencies the attention band was wider with relative as opposed to iconic cues by a factor of approximately 1.4, similar to the results of Hafter et al. (1993) and Hübner and Hafter (1995). Interestingly, however, when there were only four possible cue frequencies, the width of the attention band was virtually identical, whether cues were relative or iconic. In addition, the same listener completed a revised version of the present experiment, in which eight possible cue frequencies were presented. While there was still substantially better performance on cue-f rather than other-f trials, the size of the difference was reduced to 11.1%, compared to 23.3% when there were only four cue frequencies. Caution is necessary in drawing conclusions from the data of a single listener, particularly given the considerable variation across listeners in performance on the two types of invalidly cued trials in Experiment 3. However, this decline in the advantage for cue-f relative to other-f signals with an increase in the number of possible frequencies used, taken together with the evidence of changes in the widths of the attention bands, suggests that there may be differences in the voluntary processes involved in shifting attention to the frequency indicated by a relative cue according to the number of possible frequencies, and that these differences may determine whether involuntary effects of the cue become apparent.

One possibility is that with only a small number of possible frequencies, rather than having to calculate the frequency at which the signal is likely to appear listeners might be able to select the required frequency from memory. There is considerable evidence from studies of auditory and visual attention that whether or not involuntary cuing effects are observed can depend on which voluntary processes are being engaged (Folk, Remington, & Johnston, 1992; Folk, Remington, & Wright, 1994; Spence & Driver, 1994). It is conceivable that in relative cue conditions, involuntary effects of the cue occur when listeners are able to select the expected frequency from memory but not when they have to calculate it. Such a difference might occur because a calculation process requires more limited-capacity resources than memory recall.

The current data do not allow firm conclusions to be drawn as to why there is good performance on signals at the same frequency as the cue in the current experiment but not in Hafter et al. (1993). Importantly, though, the current results do demonstrate that, at least in certain circumstances, performance at the frequency of the cue is enhanced by an involuntary process, even when voluntary processes are operating to focus attention at a different frequency.

GENERAL DISCUSSION

Involuntary Attention in Selective Frequency Listening

The attribution of effects of uninformative cues to involuntary attention typically relies on assumptions about the strategies adopted by listeners, assumptions that may not always be valid; it can, therefore, be difficult to separate the contributions of voluntary and involuntary attentional processes. In the current experiments, though, there are good reasons to believe that involuntary attentional effects have been identified. In Experiment 1, the size of the advantage for valid over invalid trials declined, as the delay between cue and signal increased when cues were uninformative but was virtually unaffected by delay when cues were informative. No such difference would be expected if cuing effects resulted from voluntary attention to the cue frequency regardless of its predictive value. In Experiment 2, it is implausible that listeners were voluntarily attempting to heighten sensitivity at the frequency of the cue from the previous trial. In Experiment 3, the pattern of performance across the various conditions makes it highly unlikely that the enhanced detection at the cue frequency could be explained by voluntary attention to the cue frequency in addition to the expected target frequency. Taken together, the results of these three experiments provide clear evidence of involuntary attention in selective frequency listening.

They also provide further evidence that the nature of involuntary attentional processes may depend upon the attribute being attended and the particular task in question. For example, the long-lasting nature of the cuing effects found here, and the fact that involuntary effects of cues were demonstrated in situations where listeners were voluntarily focusing at other frequencies, contrast with what is typically found in studies of spatial attention, and count against the suggestion that involuntary attention in selective frequency listening should be regarded in terms of orienting in frequency space analogous to involuntary spatial orienting (Ward, 1997; see also Justus & List, 2005).

In addition, the current findings cannot straightforwardly be accounted for by a template-matching process (e.g., Mondor, Zatorre, & Terrio, 1998; Moore et al., 1996), since they show that performance is influenced not just by the frequency of the cue on a given trial, but also by that of the cue from the previous trial; and that detection at cue frequencies is enhanced even when the cue indicates that the signal is very likely to be at a different frequency. To accommodate such findings within a template-based model, it would be necessary to allow for the inclusion of different sources of frequency information within the template, with differing degrees of control over the selection process.

The results are, however, highly consistent with the proposal that, independent of listeners' intentions, detection of a particular signal is enhanced in the presence of a memory trace at the same frequency. It is possible to conceive of a number of ways in which the presence of a trace may influence detection. For example, Cowan (1988, 1995) has proposed a model addressing links between attention and memory. A key feature of this model is its hierarchical conception of the relationship between the focus of attention, which determines the contents of conscious awareness, and types of memory. The model regards short-term memory as a subset of long-term memory, consisting of the currently activated elements of long-term memory. In turn, the focus of attention is held to be a subset of this currently activated memory.

Applying this conceptualization of auditory memory to the current cued detection tasks, a plausible interpretation might be that the focus of attention is drawn to the cue, which, it is reasonable to assume, always reaches conscious awareness. Even when the listener has no desire to heighten sensitivity at the frequency of the cue, the representation of the cue will remain in currently activated memory for some considerable time. The probability of a signal being detected can be seen as reflecting the probability of the representation of that signal reaching conscious awareness—that is, becoming the focus of attention—and, as Cowan suggests, "pre-existing activation of certain features would . . . make these features more easily reached by the focus of attention" (Cowan, 1995, p. 30).

Another interesting possibility relates to the conclusion drawn from studies of the mismatch negativity (MMN) component of ERPs, that auditory sensory memory contains not just traces of recently presented stimuli but also representations of regularities in the sequence of recent auditory input (Näätänen, Tervaniemi, Sussman, Paavilainen, & Winkler, 2001; Näätänen & Winkler, 1999; Schröger, 1997; Winkler & Cowan, 2005; Winkler, Karmos, & Näätänen, 1996). This allows the development of a neural model of the auditory environment which includes "a set of processes responsible for preattentively detecting invariances in the acoustic stimulation, inferring the probable continuation of a sequence, and maintaining the model" (Winkler et al., 1996, p. 240). The MMN, which is elicited by a deviant stimulus presented after a few repetitions of a standard stimulus, is believed to reflect adjustments to the model caused by a stimulus that is inconsistent with its current inferences.

An important point is that in the current tasks, because there is a single cue on each trial, varying randomly in frequency from trial to trial, there is not a repetitive sequence of stimuli of the same frequency that would establish that frequency as a regular feature within the model. It is possible, though, to speculate that the evidence of enhanced detection at frequencies which match those of currently present sensory traces may represent the operation of processes involved in the automatic building of the model. That is, as part of a process of identifying regularities in the ongoing stream of incoming input, it would be adaptive to favor the detection of repeated features of a recently presented stimulus.

Voluntary Attention in Selective Frequency Listening

That the effect of the proportion of valid cues on the advantage for validly cued over invalidly cued trials was greater with the 10-sec than with the 1-sec delay in Experiment 1 is consistent with the idea that voluntary attention in response to an informative, direct frequency cue may involve the maintenance of the memory trace of the cue, which otherwise slowly decays. Other voluntary processes are clearly involved in making use of relative cues. The enhanced detection of signals at the cue frequency in Experiment 3 indicates that these voluntary processes did not eliminate involuntary effects of memory traces on detection. However, the contrast between this finding and the earlier results of Hafter et al. (1993), in conjunction with the additional evidence from a single listener of the role of the number of possible frequencies, raises the possibility that the extent to which the presence of a memory trace of a previous sound affects detection may depend on the nature of the voluntary attentional processes active in the particular context.

Further research is needed to investigate such possible interactions between voluntary and involuntary processes, and also to explore further the apparent differences between attention to frequency and spatial attention. It appears likely that the interpretation of attention to frequency in terms of memory processes and representations identified by ERP research can provide a useful framework for such research.

AUTHOR NOTE

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NOTES

1. For the two frequencies at the extreme ends of the possible range (0.67 and 5.0 kHz) the two frequencies at which invalidly cued signals never appeared were the next nearest frequency and the frequency at the opposite end of the range. For example, an invalidly cued signal following a cue at 0.67 kHz appeared with equal probability at any of the nine frequencies within the range 0.97–4.17 kHz, but never at 0.8 kHz or at 5.0 kHz.

2. In the no-cue condition the time between the initiation of each trial and the first observation interval was identical to that in the corresponding cued conditions. Although the cue interval was silent, we refer to these conditions as 1-sec and 10-sec delay no-cue conditions.

3. On completion of the experiment listeners were informed that there had been only two different trial orders used in the experimental conditions and asked if they had become aware of this. All four reported that they had not and that they had believed that the trials were presented in random order.

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