Effects of pulsing of a target tone on the ability to hear it out in different types of complex sounds

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Judgments of whether a sinusoidal probe is higher or lower in frequency than the closest partial (“target”) in a multi-partial complex are improved when the target is pulsed on and off. These experiments explored the contribution of reduction in perceptual confusion and recovery from adaptation to this effect. In experiment 1, all partials except the target were replaced by noise to reduce perceptual confusion. Performance was much better than when the background was composed of multiple partials. When the level of the target was reduced to avoid ceiling effects, no effect of pulsing the target occurred. In experiment 2, the target and background partials were irregularly and independently amplitude modulated. This gave a large effect of pulsing the target, suggesting that if recovery from adaptation contributes to the effect, amplitude fluctuations do not prevent this. In experiment 3, the background was composed of multiple steady partials, but the target was irregularly amplitude modulated. This gave better performance than when the target was unmodulated and a moderate effect of pulsing the target. It is argued that when the target and background are steady tones, pulsing the target may result both in reduction of perceptual confusion and recovery from adaptation. © 2012 Acoustical Society of America.
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I. INTRODUCTION

Human listeners have some ability to “hear out” individual partials in complex tones (Helmholtz, 1954; Plomp, 1964). Partial that can be heard out are often referred to as “resolved,” although there are many definitions of what is meant by “resolved” (Moore and Gockel, 2011). The ability to hear out partials depends at least partly on the sharpness of the auditory filters (Plomp, 1964; Plomp and Mimpen, 1968; Moore and Ohgushi, 1993; Moore *et al.*, 2006; Moore and Glasberg, 2011). However, other factors may also play a role. For example, the ability to hear out partials worsens at high frequencies (Moore and Ohgushi, 1993; Hartmann *et al.*, 1990; Moore *et al.*, 2006), perhaps because of the deterioration of precise phase locking in the auditory nerve (e.g., Rose *et al.*, 1967). Measures of the ability to hear out partials might also be influenced by cognitive or attentional factors (Bernstein and Oxenham, 2003). For instance, musical experience has been linked to improved performance in hearing out partials without any change in the underlying auditory filter shapes (Soderquist, 1970; Fine and Moore, 1993). Musical experience is also associated with better performance in informational masking tasks, where the ability to detect the target is limited by factors other than peripheral frequency selectivity (Oxenham *et al.*, 2003).

Studies measuring the ability of subjects to hear out partials have often used a two-alternative forced-choice task

similar to that employed by Roberts and Bregman (1991) and Moore and Ohgushi (1993). On each trial, subjects had to indicate whether a sinusoidal “probe” was higher or lower in frequency than the nearest partial in the complex tone that was presented after the probe; this is referred to as the “target” partial. In such a task, subjects may be able to hear out some partials in the complex tone but may have difficulty in deciding which of those partials is closest in frequency to the probe. This is an example of what we refer to as a “perceptual confusion” effect; performance on the task is poor not because the partials cannot be heard out but because of some other aspect of the stimuli and/or task.

Difficulty in deciding which partial in the target should be compared with the probe is illustrated by an experiment of Roberts and Bailey (1993). They presented a pure tone followed by a complex tone. The latter contained either the odd harmonics only or the odd harmonics plus a single even harmonic. Subjects were informed that a pure tone was “embedded” in the complex and were asked to judge whether the pitch of the embedded pure tone was the same as, higher than, or lower than the pitch of the isolated pure tone. Pitch jumps toward the added even harmonic were often heard when the preceding pure tone matched exactly the frequency of one of the adjacent odd harmonics; these pitch jumps were the dominant percepts for the higher harmonic numbers tested.

When a complex tone contains partials that are well separated in frequency, the complex tone may be heard as a whole (often referred to as “synthetic listening”) or pitches may be heard corresponding to the individual partials (often

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referred to as “analytic listening”) (Smootenburg, 1970; Houtsma and Fleuren, 1991; Moore, 2012). When the partials are gated on and off together, this promotes synthetic listening (Moore *et al.*, 1986). If the partials form a harmonic series, or a spectrally regular series, this also promotes synthetic listening (Moore *et al.*, 1985; Moore *et al.*, 1986; Roberts, 2005). In studies of the ability to hear out partials in complex tones, the partials in the complex tones have usually been gated on and off synchronously, and in some studies, the partials formed a harmonic series. These factors would have promoted synthetic listening, making the task more difficult even though the partials were potentially resolvable. Here such effects are also classified as a form of perceptual confusion.

To overcome difficulties associated with perceptual confusion, Bernstein and Oxenham (2003, 2006, 2008) pulsed both the probe and the target harmonic in the complex tone on and off. Pulsing the target in the complex makes the target appear to stand out from the other components in the same way that amplitude modulation of a component or group of components makes the component(s) “pop out” from a steady background (McAdams, 1982; Summerfield and Culling, 1992; Moore and Bacon, 1993). Bernstein and Oxenham (2003, page 3325) stated that the pulsing was intended “to help overcome any nonperipheral limitations and to encourage perceptual segregation, while not affecting peripheral resolvability.” For example, the pulsing may help to reduce confusion about which partial in the complex tone to compare in frequency to the probe; the partial that is pulsed must be the target. Pulsing also helps to reduce the tendency for synthetic listening.

Performance on the task of Bernstein and Oxenham was very good (>90%) for the lower harmonics but decreased with increasing harmonic number, reaching 75% correct for about the 10th harmonic, for fundamental frequencies of 100 and 200 Hz. The upper limit in harmonic number found by Bernstein and Oxenham was markedly higher than found in earlier studies, in which the target harmonic was not pulsed (Plomp, 1964; Plomp and Mimpen, 1968; Soderquist, 1970; Fine and Moore, 1993); these studies generally showed that only the lowest five to eight harmonics could be heard out with 75% or better accuracy. On the other hand, the limit found by Bernstein and Oxenham (2003) corresponds reasonably well with the point above which harmonics produce a less salient pitch, and exhibit other properties (such as phase dependence) that have traditionally been ascribed to unresolved harmonics (Houtsma and Smurzynski, 1990; Shackleton and Carlyon, 1994).

Bernstein and Oxenham (2003) assumed that the pulsing of the target would not affect peripheral resolvability. However, although peripheral tuning may not be affected, pulsing may influence the magnitude of the peripheral response to the target relative to the response to other partials in the complex sound. This in turn may have enhanced listeners’ ability to hear out the target. When a tone is presented continuously, the response of single neurons in the auditory nerve to that tone declines over time, reflecting adaptation (Kiang *et al.*, 1965; Smith, 1977; Javel, 1996). For a continuous harmonic complex tone, the responses to all harmonics

decline over time. However, when a tone is turned off and then back on again, the firing rate of single neurons often shows an initial peak when the tone is turned back on, reflecting recovery from adaptation (Smith, 1977). Similarly, if one partial in a complex tone is turned on after the remaining partials, the discharge rate of primary neurons tuned to the frequency of the delayed-onset partial is greater than the (adapted) rate of neurons tuned to the other components (Palmer *et al.*, 1995).

The effect of removing a component from a complex tone and then reinstating it is often referred to as auditory “enhancement.” The reinstated component stands out perceptually for a few seconds (Green *et al.*, 1959; Viemeister, 1980; Summerfield *et al.*, 1987; Serman *et al.*, 2008) and it produces more forward masking than a component that has been present for the whole duration of the complex tone (Viemeister, 1980; Viemeister and Bacon, 1982). The origin of the increase in forward masking is not clear. In one condition used by Palmer *et al.* (1995), a 200-Hz harmonic series lacking components near 2 kHz preceded another series with the 2-kHz component present (the “test” series). In a second condition, the test series was preceded by silence. In measurements from the guinea-pig auditory nerve, the 2-kHz component caused the same increase in firing rate for the two conditions. Palmer *et al.* concluded that there was no evidence for an increase in gain in the 2-kHz region that might lead to increased forward masking by the reinstated component. It has been suggested that the increased forward masking effect results from adaptation of suppression or inhibition at a higher level in the auditory system (Viemeister and Bacon, 1982; Scutt *et al.*, 1997; Byrne *et al.*, 2011), and a recent physiological study in the inferior colliculus of awake and passive marmosets did find some responses that exhibited the expected properties of enhancement (Nelson and Young, 2010).

In addition, the perceptual enhancement effect might not be related solely to neural firing rate. For example, Palmer *et al.* (1995) found that the proportion of the total discharge rate that was phase locked to 2 kHz was larger when the test series followed the harmonic series than when it followed silence. The sensation of the reinstated component standing out might be related to the increase in amount of phase locking to that component relative to the amount of phase locking to other components.

Whatever the mechanisms underlying auditory enhancement, it is possible that the ability of subjects to hear out the target harmonic in the experiments of Bernstein and Oxenham (2003, 2006, 2008) was enhanced by a recovery from adaptation, recovery from suppression/inhibition, and/or greater phase locking to the target produced by pulsing the target on and off. Furthermore, part of this effect may have been peripheral in origin, i.e., occurring at the level of the auditory nerve. For brevity in what follows, we refer to all such effects as “recovery from adaptation.”

Hartmann and Goupell (2006) studied the ability of subjects to make pitch matches to a pulsed harmonic in a complex tone. When subjects were allowed to listen to harmonic complex tones with different starting phases of the harmonics, they were able to select a “favorable” set of phases that allowed a selected (pulsed) harmonic to be heard

out more easily and matched in pitch more accurately than for other phase selections. For favorable phase selections, subjects could make reliable pitch matches for harmonics up to the 20th. Hartmann and Goupell argued that harmonics above the 10th would not be resolved and that the pulsing enabled pitch matching to harmonics that would not normally be resolved.

Moore *et al.* (2009) assessed the possible role of recovery from adaptation by using a similar task to that of Bernstein and Oxenham (2003, 2006, 2008), but exploring the effect of varying the interval between pulses and the rise/fall time of the pulses. They argued that if the pulsing produces a recovery from adaptation that makes the task easier, then shortening the interval between pulses or decreasing the rise/fall time of the pulses should lead to a worsening in performance because both of these manipulations would lead to a reduced recovery from adaptation (Smith, 1977, 1979; Westerman and Smith, 1984). This pattern of results was indeed found. On the basis of these results and a modeling study, Moore *et al.* (2009) proposed that the improvement in ability to hear out a partial in a complex tone produced by pulsing that partial is partly mediated by a recovery from adaptation and does not result solely from reduction of perceptual confusion. However, the effects of inter-pulse interval found by Moore *et al.* (2009) might also have occurred because when the gaps between pulses were shortened, the gaps were less salient, and this decreased the effectiveness of the pulsing in reducing the effects of perceptual confusion. Thus it remains possible that the effect of pulsing a partial depends on recovery from adaptation, reduction of perceptual confusion, or both. Indeed the putative reduction of perception confusion might depend partly on recovery from adaptation.

In the present paper, we tried to assess the relative importance of recovery from adaptation and reduction of perceptual confusion by examining the effect of pulsing the target on performance for various types of background sounds. The task was similar to that used by Moore *et al.* (2009); subjects had to say whether the “target” component in the complex sound was higher or lower in pitch than a previously presented probe. The study used as a starting point complex tones with partials uniformly spaced on the ERB_N-number (*Cam*) scale (see following text for details) as employed by Moore *et al.* (2009). The tones were therefore inharmonic. This made it very unlikely that the results would be influenced by the starting phases of the components (Hartmann and Goupell, 2006).

In the first experiment, the “background” partials in the complex tone (i.e., all partials except the target on a given trial) were replaced by noise. The noise used in a given trial had a narrow spectral notch around the frequency of the target. The level of the noise and the width of the notch were chosen so that the excitation pattern evoked by the noise and the effective target-to-background ratio were both very similar to those produced by the complex-tone background used by Moore *et al.* (2009). The rationale for using this background was that it should reduce perceptual confusion effects because there was only one tonal component in the complex sound. If the effect of pulsing the partial is mainly

to reduce perceptual confusion, then the effect of pulsing should be small with the noise background as there is little confusion to begin with.

II. EXPERIMENT 1: EFFECT OF REPLACING THE BACKGROUND TONES WITH A NOISE

A. Method

The method was similar to that used by Moore *et al.* (2009). On each trial, subjects were presented with a sinusoidal probe tone followed by a complex sound. Subjects were told that the probe was close in frequency to a tone in the complex sound (the target) but was actually slightly higher or lower in frequency than the target. On half the trials, chosen at random, the probe was higher in frequency than the target by 4.5%, and on the other half, it was lower by 4.5%. Subjects were asked to indicate, by pressing the appropriate button on the response box, whether the target was higher or lower in frequency than the probe. Correct-answer feedback was provided after each trial by lights on the response box. The nominal frequency of the target was selected randomly on each trial from 1 of 11 possible values. The actual frequencies of all targets in the complex sound were randomly varied (roved) from trial to trial by multiplying the nominal frequencies by a factor randomly chosen within the range 0.9 to 1.1, while keeping the frequency ratios between possible frequency values fixed. The frequency of the probe was multiplied by the same factor. The roving was done to prevent subjects from learning the correct response associated with a specific probe frequency (Soderquist, 1970).

Each possible target frequency was probed 10 times in a given run, 5 times with the probe lower in frequency than the target and 5 times with it higher. Five runs were obtained for each pulsing condition, giving a total of 50 judgments for each target frequency.

B. Stimuli

The target frequency was chosen randomly on each trial from 1 of 11 possible values that were spaced at 1-*Cam* intervals. The relationship between *Cams* and frequency, *f* (Hz), was assumed to be as suggested by Glasberg and Moore (1990):

$$Cam = 21.4 \log_{10}(0.00437f + 1) \quad (1)$$

The mean frequency of the central target was always 1201 Hz, corresponding to *Cam* = 17. The nominal frequencies of the possible targets were: 605, 700, 806, 924, 1055, 1201, 1364, 1545, 1747, 1972, and 2222 Hz.

It was desired to create an excitation pattern for the noise background on each trial that was as similar as possible to that evoked by the background tones used by Moore *et al.* (2009) for the 1-*Cam* spacing. This is based on the assumption that the salience of the target would be determined by the effective target-to-background ratio. The background tones used by Moore *et al.* each had a level of 50 dB SPL. The starting point for matching the excitation patterns was a noise with a constant level in each 1-*Cam* wide band. We

call this “equal-Cam-density noise” (ECDN); it is similar to, but not exactly the same as, threshold equalizing noise (Moore *et al.*, 2000). Excitation patterns were calculated using the method described by Glasberg and Moore (1990). It was found that an ECDN extending from 561 to 2357 Hz, with a level of 51 dB/Cam produced an excitation pattern very similar to that for the 11-tone complex used by Moore *et al.* (2009). The excitation level was between 52 and 52.5 dB over the frequency range from 600 to 2000 Hz.

It was also desired to match the target-to-background ratio produced by the background tones and the noise at the output of the auditory filter centered at the target frequency. To achieve this, a small spectral notch was placed around the target frequency. The spectral position of the notch varied from trial to trial, so that it was always centered at the target frequency. To illustrate how the appropriate notch width was calculated, consider the central nominal target frequency of 1201 Hz. When the 50-dB SPL target at 1201 Hz was removed from the 11-tone complex, the excitation level at 1201 Hz dropped to about 45 dB, meaning that the effective target-to-background ratio was about 5 dB. When a spectral notch was introduced into the noise, from 1110 to 1290 Hz (a range corresponding to 1.18 Cams), the excitation level at 1201 Hz was 44.9 dB, very close to that produced by the complex tone with the 1201-Hz component missing. By adding a 50-dB SPL target to the background noise, the desired target-to-background ratio of 5 dB was achieved, and the excitation pattern for the target-plus-background was very close to that for the 11-tone complex used by Moore *et al.* (2009). In summary, the background noise was an ECDN with a level of 51 dB/Cam with a 1.18-Cam wide spectral notch centered at the target frequency on each trial. The probe and the target both had a level of 50 dB SPL.

The probe and the complex sound (target plus background noise) each had an overall duration of 1000 ms with 20-ms raised-cosine rise/fall ramps. The inter-stimulus interval was 300 ms. The noise was always uninterrupted for the 1000-ms duration. In one condition, the probe and the target were also uninterrupted for the 1000-ms duration. This condition is similar to one used previously by Moore *et al.* (Moore *et al.*, 2006; Moore *et al.*, 2009) with multi-partial backgrounds. In the other condition, both the probe and the target were pulsed off and on with the same off-on pattern for the two. Each pulse had 20-ms raised-cosine ramps and a 226.7-ms steady duration. The temporal gap between pulses, measured between the half-amplitude points, was 100 ms. This condition is the same as one used by Moore *et al.* (2009). When the experiment was planned, it was also intended to use conditions with smaller gaps. However, as described in the following text, pilot experiments indicated little effect of the pulsing, so it was decided to use only the two extreme conditions.

Stimuli were generated digitally using a Tucker-Davis Technologies (TDT) System II. The stimuli were played through a 16-bit digital-to-analog converter (TDT, DD1) at a 50-kHz sampling rate, low-pass filtered at 8 kHz (Kemo VBF8/04), attenuated (TDT, PA4), and presented via a headphone buffer (TDT, HB6), a manual attenuator (Hatfield 2125), and one earpiece of a Sennheiser HD580 headphone,

which has a diffuse-field response. Levels specified are equivalent diffuse-field levels. Levels at the eardrum would have been higher for frequencies around 3000 Hz (Moore *et al.*, 1998). Subjects were tested individually in a double-walled sound-attenuating chamber.

C. Subjects

In all experiments, the subjects had no reported history of hearing disorders, had absolute thresholds better than 20 dB HL for audiometric frequencies from 250 to 8000 Hz (ISO 389-8, 2004), and had some degree of musical training. All subjects had extensive experience in similar tasks. They were given 1-2 h of training with the specific stimuli used before data collection proper began. Author B.G. took part in all experiments. All subjects except B.G. were paid for their participation. In experiment 1, five subjects (four male, one female) were used. Their ages ranged from 25 to 64 yr.

D. Results and discussion

Initial runs indicated that with the noise and target tone parameters set as described in the preceding text, the task was very easy. Performance was close to ceiling whether or not the probe and target were pulsed. Performance was much better than measured by Moore *et al.* (2009) using a background of tones with 1-Cam spacing despite the fact that calculated excitation patterns were very similar for the background noise used here and for the background tones used by Moore *et al.* This is consistent with the idea that perceptual confusion, and especially difficulty in deciding which component in the complex tone to compare to the probe, made the task more difficult when the background was composed of multiple tones.

To allow a meaningful evaluation of the effects of pulsing the target in the noise and to reduce ceiling effects, it was necessary to make the task more difficult. This was done either by reducing the level of the target slightly or by making the spectral notch around the target frequency narrower or both. Pilot experiments were conducted to determine appropriate combinations of target level and notch width for each subject; two or three combinations were selected for each subject. The values used with each subject are shown in columns 2 and 3 of Table I.

For analysis and presentation of the data, the scores for a given subject and a given condition were averaged across all combinations of target level and notch width used for that subject. This gave a single score for each partial, each pulsing condition, and each subject. The averages of the scores obtained in this way are shown in Fig. 1. The results showed a somewhat irregular pattern, as found in previous studies (Moore and Ohgushi, 1993; Moore *et al.*, 2006; Moore *et al.*, 2009). There was no clear trend for performance to differ across the two pulsing conditions. A within-subjects analysis of variance (ANOVA) was conducted with factors partial number and pulsing condition. The effects of partial number and of pulsing condition were not significant. The interaction between partial number and pulsing was significant [$F(10,40) = 3.63$, $P = 0.002$], but it accounted for only about 3% of the variance in the data. Performance tended to be

TABLE I. Scores (percent correct) for experiment 1 averaged across the inner partials for the condition where the target tone was presented as a single pulse, and where it was presented as three pulses separated by 100-ms gaps. The width of the notch in the background noise and the level of the target tone were chosen separately for each subject on the basis of pilot trials in an attempt to give performance in the range between 55% and 95% correct; two or three combinations were used for each subject. SD means standard deviation.

Subject	Notch width, <i>Cams</i>	Target level, dB SPL	Percent correct	
			One pulse	Three pulses
1	1.18	48	88.3	82.7
	1.00	48	86.9	66.8
	1.00	50	92.0	77.2
2	1.18	48	66.4	79.4
	1.18	50	73.1	86.3
3	1.18	48	83.1	85.2
	1.00	48	59.6	58.3
4	1.00	48	54.9	47.2
	1.00	50	74.9	67.6
5	1.00	48	58.7	56.1
	1.00	50	83.3	80.0
Mean (SD)			74.7 (13.1)	71.5 (13.2)

better for the steady than for the pulsed partial for partial numbers up to 6, but Bonferroni corrected *post hoc* comparisons showed that the difference was not significant for any partial number.

To obtain an overall measure of performance, the mean scores across the inner partials were averaged for each subject and each combination of notch width and target level. The scores for the lowest and highest partials were excluded

FIG. 1. Scores averaged across subjects for experiment 1 in which the target was a tone, and the background was a noise with a small notch at the target frequency. The percentage correct is plotted as a function of partial number. The probe tone and the target tone within the complex sound were either presented as a single long pulse (crosses) or as three pulses with 100-ms gaps (circles) (illustrated schematically at the top).

as these were close to ceiling for some subjects. The results are shown in Table I. Only one subject (subject 2) showed a trend for better performance with three target pulses than with a single longer target pulse. In the mean data, there was a slight (non-significant) trend in the opposite direction. Thus the results are very different from those of Moore *et al.* (2009) that were obtained using a background of tones rather than noise; Moore *et al.* found much better performance for the three-pulse condition than for the one-pulse condition.

These results appear to support the idea that the large effect of pulsing the target partial found by Moore *et al.* (2009) largely reflected a reduction of perceptual confusion. In the present experiment, such confusion would have been minimal owing to the use of a noise background rather than a background composed of multiple tones. However, there are some other possible explanations for the failure to find an effect of pulsing the target in experiment 1. First, the failure may have been a consequence of the fact that the changes in excitation level produced by the pulsing were small. Recall that to reduce performance below ceiling, it was necessary to reduce the width of the spectral notch in the noise background and/or to reduce the level of the tone relative to what would have been necessary to match excitation patterns for the tone and noise backgrounds. This meant that when the target was turned off and on to produce the pulsing, there were relatively small changes in excitation level at the target frequency. Recovery from adaptation presumably depends on the extent to which the excitation level is reduced during “off” periods; if the reduction is too small, the recovery from adaptation may be negligible.

A second possible explanation for the failure to find an effect of pulsing the target in experiment 1 is that the fluctuations in amplitude produced by the noise background at the output of the auditory filter centered on the target frequency reduced or eliminated the effects of adaptation and recovery from adaptation. Consistent with this idea, it is known that perceptual adaptation (reduction in loudness) produced by prolonged exposure to a steady sound is much less for a band of noise, which has inherent random amplitude fluctuations, than for a steady tone (Scharf, 1983). The idea that fluctuations in amplitude lead to reduced adaptation and recovery from adaptation was tested in experiment 2.

III. EXPERIMENT 2: EFFECT OF PULSING THE TARGET PARTIAL WHEN ALL PARTIALS HAVE NOISE-LIKE AMPLITUDE MODULATION

A. Rationale and method

If amplitude fluctuations produced by the background noise lead to reduced adaptation and recovery from adaptation, and if recovery from adaptation contributes to the effect of pulsing the target when a background composed of multiple partials is used, then amplitude modulating all of the partials (including the target) should reduce or eliminate the effect of pulsing the target partial. That idea was tested using stimuli very similar to those of Moore *et al.* (2009); the complex sound on each trial was composed of 11 sinusoidal components spaced at 1-*Cam* intervals. However, in experiment 2, all components in the complex sound were amplitude

modulated. The probe tone presented before the complex sound was not amplitude modulated (except for any modulation produced by the pulsing, as described below). As for experiment 1, the target frequency was varied randomly from trial to trial.

It was desired that the amplitude modulation applied to each partial should resemble the inherent modulation produced by the background noise used in experiment 1. The waveform of the amplitude modulator applied to a given partial was derived as follows. An ECDN was passed through a fourth-order gammatone filter (Patterson *et al.*, 1995) centered at the frequency of the partial; this was done separately for each possible partial frequency. The Hilbert envelope (Bracewell, 1986) of the filter output was extracted and a 1-s segment was stored. For a given partial, the 1-s envelope segment extracted from the filter centered at the frequency of that partial was used as the modulator. The modulator was fixed (frozen) for each partial but was different across partials. The number of maxima/s in the modulator was approximately 0.78ERB_N (Glasberg and Moore, 1990). For example, for the center partial at 1201 Hz, for which ERB_N is 154 Hz, the modulator had 120 maxima/s.

The root-mean-square (RMS) level of each modulated tone in the background and the RMS level of the target tone was 50 dB SPL, the same as used by Moore *et al.* (2009). The following conditions were used, all with raised-cosine ramps, as shown in the legend of Fig. 2 (note that these ramp times refer to the ramps *within* the pulsing pattern; the very first and very last ramps always lasted 20 ms). All gap durations are specified at half-amplitude points. The probe and the target both:

- (1) were uninterrupted for the 1000-ms duration (single pulse)
- (2) had 10-ms ramps, 10-ms gaps, and 306.7-ms steady pulse duration
- (3) had 20-ms ramps, 20-ms gaps, and 293.3-ms steady pulse duration
- (4) had 20-ms ramps, 50-ms gaps, and 260-ms steady pulse duration
- (5) had 20-ms ramps, 100-ms gaps, and 226.7-ms steady pulse duration

(5) had 20-ms ramps, 100-ms gaps, and 226.7-ms steady pulse duration

Other details of the stimuli, method, and equipment were as described for experiment 1.

B. Subjects

Five subjects (three male) participated, three of whom took part in experiment 1. Their ages ranged from 24 to 64 yr.

C. Results and discussion

There were marked individual differences and irregularities in the results. However, for all subjects, there was a clear trend for performance to improve with increasing gap duration. The mean scores across subjects are plotted in Fig. 2. Although there appears to be a cyclic pattern as a function of partial number, this is probably just a coincidence. Previous results using a similar task suggest that performance varies in an unpredictable way with partial number and that the pattern of the irregularity usually varies from one subject to another (Moore *et al.*, 2006). A within-subjects ANOVA was conducted with factors partial number and pulsing condition. There was a significant effect of partial number [$F(10,40)=3.98$, $P<0.001$] and of pulsing condition [$F(4,16)=62.19$, $P<0.001$]. The interaction was also significant [$F(40,160)=1.99$, $P=0.001$].

It is clear that there is a substantial effect of pulsing the target. The scores averaged across the inner partials are shown by the triangles in Fig. 3; as before, results for the edge partials were excluded because, at least for the lowest partial, they were probably influenced by ceiling effects. For comparison, the results obtained by Moore *et al.* (2009) using very similar stimuli but without any modulation applied to the partials are shown by the circles. The overall effect of pulsing the target was smaller for experiment 2 (change in performance from 63% to 87%) than reported by Moore *et al.* (change from 56% to 93%). To assess the significance of this difference, an ANOVA was conducted with

FIG. 2. Scores averaged across subjects for experiment 2 in which the background was composed of multiple partials, and all partials in both the target and background were irregularly and independently amplitude modulated. The percentage correct is plotted as a function of partial number. Each symbol shows results for one pulsing condition of the probe and target. The conditions are indicated schematically on the right.

FIG. 3. Comparison of results from experiment 2 (triangles), experiment 3 (squares), and Moore *et al.* (2009, circles). Mean scores for the nine inner partials are plotted as a function of the duration of the gaps in the probe and target.

gap duration and partial number as within-subjects factors and presence or absence of amplitude modulation as a between-subjects factor.¹ There were significant effects of gap duration [$F(4,32) = 238.2$, $P < 0.001$] and partial number [$F(8,32) = 25.0$, $P < 0.001$], but the effect of presence/absence of modulation was not significant [$F(1,32) = 3.1$, $P = 0.088$]. However, the interaction between gap duration and presence/absence of modulation was significant [$F(4,32) = 8.99$, $P < 0.001$], confirming that the effect of varying the gap duration was greater when all components were unmodulated than when they were amplitude modulated. There are at least three possible reasons for the reduced effect in the presence of amplitude modulation: first, the amplitude modulation applied to the partials in experiment 2 may have reduced the effects of recovery from adaptation somewhat; second, the amplitude modulation led to some time periods during which the target was higher in level than the surrounding components, making it more salient even when it was not pulsed; and third the amplitude modulation may have partially masked the modulation energy introduced by the pulsing (Dau *et al.*, 1997).

The fact that a substantial effect of pulsing the target occurred in experiment 2 indicates either that recovery from adaptation occurred despite the imposed amplitude modulation or that the effect of pulsing the target was caused by reduction of perceptual confusion or both.

IV. EXPERIMENT 3: EFFECT OF PULSING THE TARGET PARTIAL WHEN ONLY THE TARGET HAD NOISE-LIKE AMPLITUDE MODULATION

A. Rationale and method

In experiment 2, all partials in the complex sound were independently and irregularly amplitude modulated. In experiment 3, only the target was amplitude modulated, the background components being steady. The rationale for experiment 3 was that the amplitude modulation of the target should provide a strong cue for perceptual segregation of the target from the background. Modulation of one partial in a background of other partials with constant amplitudes seems

to be effective in helping to make the modulated partial “stand out” as a separate auditory object (McAdams, 1982; Summerfield and Culling, 1992; Moore and Bacon, 1993). If a smaller effect of pulsing the target was found under these conditions, that would provide further support for the idea that perceptual confusion is an important factor: Amplitude modulation should reduce the perceptual confusion and should therefore reduce any additional effect provided by the pulsing. On the other hand, if the effect of pulsing can be mainly attributed to recovery from adaptation, then the modulation of the target should not strongly affect the results, as experiment 2 showed that overall modulation produced only a small decrease in the effect of pulsing.

Experiment 3 was similar to experiment 2 except that only the target was irregularly modulated. The modulator for each target frequency was constructed as described for experiment 2, using the Hilbert envelope of the signal at the output of a gammatone filter centered at the target frequency in response to an ECDN. Other details of the stimuli, method, and equipment were as described for experiment 2.

B. Subjects

Seven subjects (three male) participated, three of whom took part in experiment 1 and four of whom took part in experiment 2. Their ages ranged from 21 to 64 yr.

C. Results and discussion

The pattern of the results varied somewhat across subjects. For example, one subject showed especially poor performance for partial number 2, one for partial number 6, one for partial number 7, two for partial number 9, and two for partial number 10. Such individual differences have been described before for a similar task (Moore *et al.*, 2006). However, for all subjects, performance improved with increasing gap duration. The mean results across subjects are shown in Fig. 4 for each condition of pulsing. Performance was poorest when the target was presented as a single long pulse (crosses) and was best when the target was pulsed

with 100-ms gaps (circles). A within-subjects ANOVA was conducted with factors partial number and pulsing condition. There was a significant effect of partial number [$F(10,60)=8.23$, $P<0.001$] and of pulsing condition [$F(4,24)=23.56$, $P<0.001$]. The interaction was also significant [$F(40,240)=2.76$, $P<0.001$].

When the target was presented as a single pulse, or was pulsed with very short gaps between pulses, performance was markedly better in experiment 3 than in experiment 2. This is consistent with the hypothesis that the amplitude modulation of the target used in experiment 3 provided a cue that aided perceptual segregation of the target from the background partials. The scores obtained in experiment 3 were also markedly higher than the scores obtained by Moore *et al.* (2009) using very similar stimuli for the conditions where the target was presented as a single pulse or was pulsed with very short gaps. This is illustrated in Fig. 3, which shows mean scores for the inner partials, plotted as a function of the duration of the gap in the probe and target for experiment 3 (squares) and for the data of Moore *et al.* (2009, circles). The only difference between the two experiments (apart from the subjects, three of whom were actually common to the two experiments) was that the target component was irregularly amplitude modulated in experiment 2, but it was not modulated in the experiment of Moore *et al.* (apart from any modulation produced by the pulsing).

To assess the significance of the effects described in the preceding text, an ANOVA was conducted with gap duration and partial number as within-subjects factors and type of amplitude modulation (none, all partials, or target partial only) as a between-subjects factor.¹ There were significant effects of gap duration [$F(4,64)=294.5$, $P<0.001$], partial number [$F(8,64)=34.6$, $P<0.001$], and type of modulation [$F(2,64)=138.2$, $P<0.001$]. *Post hoc* tests (Bonferroni corrected) showed that performance was significantly better when only the target was modulated than when no partials were modulated or all partials were modulated (both $P<0.001$). The interaction between gap duration and type of modulation was significant: $F(8,64)=20.2$, $P<0.001$.

These results support the idea that the modulation applied to the target in experiment 3 did effectively reduce perceptual confusion. The remaining effect of pulsing the target may have arisen from recovery from adaptation but may also have been due to the modulation not fully eliminating perceptual confusion. Neff (1995) found that amplitude modulation improved signal detection in a task involving informational masking (using random-frequency multi-tone maskers), but the effect was not consistent across subjects. Two of four subjects showed a reduction in masked threshold of about 8 dB for maskers with a small number of components. The other two subjects showed little effect, but one of those showed little informational masking even for an unmodulated sinusoidal target. These results suggest that amplitude modulation may not eliminate perceptual confusion for all subjects. Note that Neff used 100% modulation, whereas in this study, less modulation energy was imposed on the target, making it more likely that full segregation did not occur. On the other hand, the inconsistent effect found by Neff might have been partly a consequence of the use of a relatively short signal (200 ms). The signal duration used here was much longer (1000 ms), which would tend to make the modulation more effective as a cue.

Hall and Grose (1991) also proposed that amplitude modulation is not always an effective segregation cue. They asked listeners to detect amplitude modulation on one of two simultaneously presented carriers, at 1 and 2 kHz, and to identify which carrier was being modulated. In some conditions, listeners were able to detect the presence of amplitude modulation but were not able to identify which carrier was being modulated. While this might be taken as indicating that listeners could not use the modulation to segregate the two tones, another interpretation was offered by Moore and Bacon (1993). They found that the ability to identify a modulated carrier in a background of unmodulated components was better when the complex sound contained six components than when it contained two components. They argued that for the six-carrier complex, the modulation served to define uniquely which carrier was different from the rest; subjectively, the modulated carrier segregated from

FIG. 4. As Fig. 2 but showing scores for experiment 3 in which only the target had irregular amplitude modulation.

the other carriers. For the two-carrier complex, the modulation of one carrier may have promoted perceptual segregation of the two carriers, but this in itself was not sufficient to define which one was modulated. Given that the background in experiment 3 contained multiple partials, the modulation probably would have promoted perceptual segregation of the target from the background as described by Moore and Bacon (1993).

Overall, it seems likely that the modulation of the target in experiment 3 did reduce perceptual confusion. Despite this, there was a clear and significant effect of pulsing the target on and off. The effect of pulsing the target found in experiment 3 may have arisen partly from recovery from adaptation when the target was pulsed (Moore *et al.*, 2009). The larger overall effect of gap duration found by Moore *et al.* may indicate that in their experiment the pulsing had two effects: It produced a recovery from adaptation and it helped to resolve perceptual confusion.

V. GENERAL DISCUSSION AND CONCLUSIONS

In experiment 1, the background sound was a noise with a narrow notch at the target frequency. The noise was designed to minimize perceptual confusion effects. This led to markedly better performance than obtained by Moore *et al.* (2009) with a background of multiple inharmonic partials despite the fact that the noise level and notch width were chosen to match the excitation produced by the background partials in the experiment of Moore *et al.* and to match the effective target-to-background ratio. This finding suggests that perceptual confusion effects play a strong role when a background of tonal partials is used. When the task in experiment 1 was made more difficult, to avoid ceiling effects, by reducing the notch width and/or the level of the target, no significant effect of pulsing the target on and off was found. This lack of effect may have been a consequence of two (not mutually exclusive) factors: (1) the use of a noise background meant that there was little or no perceptual confusion, so pulsing the target was not necessary to resolve perceptual confusion; (2) the pulsing of the target produced negligible recovery from adaptation. The negligible recovery from adaptation may have occurred either because only small changes in excitation level were produced by pulsing the target on and off or because the fluctuations in amplitude produced by the background noise reduced the effects of adaptation and recovery from adaptation.

These results can be compared with those of Bregman *et al.* (1994). They asked subjects to identify the presentation order of two successive amplitude increments (duration = 1 s) on different harmonics of a 3.5-s-long complex tone. Performance was better for faster than for slower rise times of the increments over the range 40–490 ms. They argued that a sudden amplitude change may “reset” the pitch analysis system so that the incremented harmonic perceptually dominates the new analysis (in comparison with the unchanged components). In contrast, only a small and inconsistent decline in discrimination was found for longer rise times when the complex-tone background was replaced by a broadband noise. They argued that the effect of rise time

was far smaller in a background of noise because onset responses in the auditory system are triggered not only by the target tones but also by the fluctuations inherent in the noise. This provides another possible explanation for the lack of effect of pulsing found in experiment 1.

Experiment 2 tested the possibility that amplitude fluctuations at the output of the auditory filter centered at the target frequency reduce adaptation and recovery from adaptation. In this experiment, the background was composed of inharmonically spaced sinusoidal partials. Both the target and the background partials were independently and irregularly amplitude modulated. Large effects of pulsing the target were found, indicating that if recovery from adaptation plays a role, amplitude fluctuations do not prevent such recovery occurring. Alternatively, the large effects may indicate that reduction of perceptual confusion produced by the pulsing is the dominant effect. The effect of pulsing the target found in experiment 2 was slightly smaller than found by Moore *et al.* (2009) when all partials were unmodulated. This may indicate: (1) that amplitude modulation does slightly reduce the effects of adaptation and recovery from adaptation, (2) that independent modulation of the partials provides “glimpses” of the single-burst target, thereby improving performance, or (3) that the modulation energy in the target and maskers masks some of the modulation energy associated with the pulsing (Dau *et al.*, 1997). Further work is needed to distinguish between these possibilities.

In experiment 3, the background was composed of inharmonically spaced steady partials, while the target was irregularly amplitude modulated. The results showed significantly better performance when the target was pulsed than when it was presented as a single long burst. Performance was markedly better than obtained in experiment 2 for the conditions where the target was not pulsed or was pulsed with very short gaps. This difference between the two experiments supports the idea that the irregular modulation of the target in experiment 3 provided a cue that allowed perceptual segregation of the target from the background, hence reducing perceptual confusion, even when the target was not pulsed. The remaining effect of pulsing may be due to the target modulation not being fully effective in perceptually segregating the target, or to recovery from adaptation or both.

The effects of amplitude modulation of the target found in experiment 3 may be similar to those occurring when an otherwise steady target is pulsed. In experiment 3, although the RMS level of the target was matched to the level of each background partial, the short-term level of the target would sometimes have been above that of each background partial and sometimes below. The improved ability to hear out the target when it was modulated may have been partly due to “glimpses” of the target obtained when its level was momentarily above that of the background partials. In the experiment of Moore *et al.* (2009), no modulation was applied to the target (except for the pulsing). Thus the RMS level of the target was actually a little below that of each background partial when the target was pulsed and its short-term level was never above that of each background partial. However, because of the effects of adaptation and recovery from

adaptation, the *effective* level of the target may have been above that of each background partial at times just after the gaps. For both cases (modulation of the target or pulsing of the otherwise steady target), the amplitude fluctuations probably aided the perceptual segregation of the target from the background, hence reducing perceptual confusion.

In summary, the results from all three experiments can be explained in terms of effects related to perceptual confusion, as defined in the introduction, without necessarily invoking adaptation. Nevertheless, the experiments do not rule out the possibility that peripheral neural adaptation also plays a role. Therefore the results do not allow us to determine unambiguously whether results obtained using the pulsed-target method of Bernstein and Oxenham (2003) are influenced by effects of recovery from adaptation. In any case, the method clearly has limitations. First, it cannot be used to predict the ability of listeners to hear out partials when they are all gated on and off together. Second, in common with methods that do not involve pulsing of the target partial (Moore and Ohgushi, 1993; Moore *et al.*, 2006), the results probably do not reflect solely the filtering that occurs in the auditory periphery. For example, Santurette and Dau (2011) found that listeners had difficulty hearing out pulsed partials at high frequencies (6 kHz and above). They concluded that the partials were not peripherally resolved; however, it may be that the task of hearing out harmonics is only possible for lower frequencies, as has been found when the target was not pulsed but was presented in a complex sound with widely spaced partials (Moore *et al.*, 2006). Thus failure to hear out a partial from within a complex tone does not necessarily imply that the partial is unresolved in the auditory periphery, whether or not the partial is pulsed.

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¹It is not strictly correct to treat the type of modulation as a between-subjects factor as some subjects were common across experiments. However, this is a conservative approach, as it is less likely that a significant effect will be obtained when type of modulation is treated as a between-subjects factor than when it is treated as a within-subjects factor.

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