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Does selective attention influence the octave illusion?

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Abstract. The octave illusion occurs when each ear receives a sequence of tones alternating by one octave, but with different frequencies in each ear. Most listeners report a high pitch in one ear alternating with a low pitch in the opposite ear. Deutsch and Roll proposed an influential suppression model of the illusion in which the pitch is determined by ear dominance, while the location of this pitch is determined by high-frequency dominance. Deutsch later suggested that this unusual division between 'what' and 'where' mechanisms is facilitated by sequential interactions within the eliciting sequence. A recent study has raised doubts about the suppression model and the role of sequential interactions in the illusion (Chambers et al, 2002 *Journal of Experimental Psychology: Human Perception and Performance* **28** 1288 – 1302). Here, we examined whether this previous null effect of sequential interactions may have arisen because of uncontrolled influences of selective attention. The results reveal no evidence of a link between selective attention and sequential interactions, thus consolidating doubts about the validity of the suppression model.

1 Introduction

The octave illusion is an auditory perceptual phenomenon that arises when each ear receives a sequence of tones alternating in frequency by one octave, but with the high-frequency and low-frequency tones in different ears (figure 1a). Most listeners are unable to correctly identify this stimulus and instead perceive a high pitch in one ear

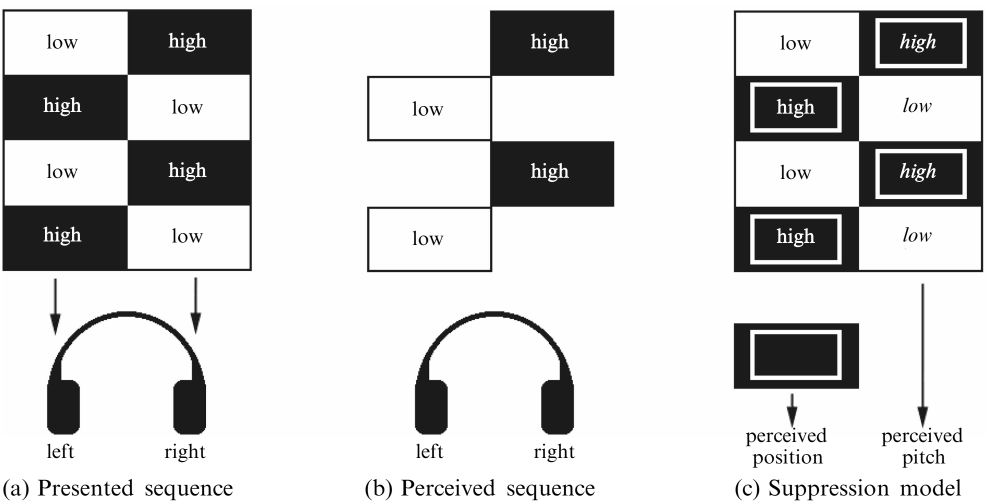

Figure 1. The octave illusion is elicited by a dichotic sequence that continuously alternates by one octave, but with different frequencies in each ear (a). Most listeners perceive this sequence as a high pitch in one ear alternating with a low pitch in the opposite ear (b). The suppression model (c) proposes that the perceived pitch is equivalent to the frequency in the dominant ear (italicised), but that this pitch is localised in whichever ear received the higher frequency tone (white border). Figure taken from Chambers et al (2002).

alternating with a low pitch in the opposite ear (figure 1b). According to the *suppression model*, the octave illusion arises from competing mechanisms governing object-based and location-based perceptual mechanisms (Deutsch and Roll 1976). Deutsch and Roll suggested that the pitch of the illusion follows the sequence of frequencies received by the listener's dominant ear, but that this pitch percept is localised in whichever ear received the higher-frequency tone (figure 1c). Conflict between 'what' and 'where' mechanisms therefore arises when the lower-frequency tone is presented to the dominant ear. In this case, the theory predicts that listeners perceive only the lower-frequency tone, but localise it in the ear that received the higher frequency.

Although parsimonious, the predictions of the suppression model contrast in two important ways with psychoacoustic literature on pitch perception and ear dominance. First, the suppression model is inconsistent with research indicating that the pitch of harmonic complex tones generally approximates the fundamental frequency (f_0), rather than the frequency in one ear. This finding is robust across a range of stimulus parameters and has been demonstrated for stimuli presented monotically (Schouten 1940a, 1940b, 1940c; Plomp 1967; Moore et al 1985; for review, see Moore 1997), dichotically (Houtsma and Goldstein 1972; Houtsma 1979; Arehart and Burns 1999) and even for complexes in which the components have non-simultaneous onsets (Hall and Peters 1981; Ciocca and Darwin 1999). Second, the suppression model is inconsistent with the results of studies on ear dominance for pitch in dichotic, inharmonic complexes (eg Efron and Yund 1974). Gregory et al (1983), for instance, showed that when pitch is determined by ear dominance, the perceived pitch is never equivalent to the frequency in one ear. Instead, the pitch may be biased 20% – 60% in the direction of the dominant ear. This result contrasts with the suppression model, which assumes an extreme ear dominance in which the dominant ear "exercises a steady suppression on the other [ear], so that only the frequencies arriving at one ear are heard" (Deutsch and Roll 1976, page 24).

To account for these discrepancies, Deutsch (1978, 1980, 1988) suggested that repeated alternation of the same frequencies between the ears facilitates suppression. This conclusion was based on subjective reports of sequences in which the difference in amplitude between left and right stimuli was varied by up to 15 dB SPL. Briefly, Deutsch noted that subjective reports remained more consistent in the face of dichotic amplitude differences (a) for longer sequences of alternating dichotic octaves relative to shorter sequences, and (b) for sequences in which the same components repeatedly alternated between the ears, relative to sequences of identical length in which the components differed. On this basis, Deutsch suggested that sequential interactions strengthen suppression, and presumably eliminate harmonic fusion. Thus, in the face of conflicting literature, the validity of the suppression model depends critically on the influence of sequential interactions.

Chambers et al (2002, in 2004a, 2004b) have since raised theoretical and empirical objections to Deutsch's (1978, 1980, 1988) conclusion that the octave illusion is influenced by sequential interactions [see also Yund (1982) and Deutsch (2004a, 2004b) for further coverage of this debate]. From a methodological perspective, any unambiguous interpretation of subjective reports is problematic because of uncontrolled response bias. This issue is of particular concern for a paradigm in which the sole dependent variable is the *consistency* of subjective reports. Rather than reflecting any change in the perception of the octave illusion, differences in subjective report consistencies could indicate a different level of response bias or response criterion. A reduction in subjective report consistency could also reflect an increase in decision noise. For example, Deutsch (1978) noted that subjective reports of the illusion were more consistent for a sequence of 20 dichotic octaves than for a sequence of 2 dichotic octaves. However, rather than reflecting an influence of sequential interactions on perception, this result could indicate that presenting listeners with less information in the 2-octave condition introduced a decision noise that reduced the certainty, and thus consistency, of the response.

Chambers et al (2002) examined the role of sequential interactions in the octave illusion in an objective psychophysical experiment. Listeners were presented with a dichotic complex tone and, in different blocks of trials, identified which ear received the higher or lower frequency. This task was undertaken for four harmonic interval ratios, including 1.3 (fourth), 1.5 (fifth), 2 (octave), and 4 (double octave). These harmonic ratios were fully crossed with three sequencing conditions: (i) nonsequenced, in which the segregation task was undertaken on a single stimulus; (ii) repeated sequence, in which the segregation task was undertaken after 20 repetitions of the same dichotic complex; and (iii) alternating sequence, in which the segregation task was undertaken after 20 alternations of the same dichotic complex between ears.

Chambers et al (2002) predicted that if suppression is influenced by sequential interactions, then, during the sequence that elicits the octave illusion, performance in the alternating-sequence condition should be reduced relative to performance in the nonsequenced condition. This hypothesis followed from the prediction of the suppression model that sequential interactions increase ear dominance, thus encouraging suppression of the frequency in the nondominant ear and increasing the difficulty with which the stimuli in each ear could be segregated and compared. This hypothesis, however, was not supported; performance in the nonsequenced and alternating-sequence conditions did not differ significantly. Thus, sequential interactions did not appear to influence the perceptual salience of the components within single dichotic octaves, contrary to the predictions of the suppression model.

Although the study by Chambers et al (2002) raises significant doubts about the role of sequential interactions in the octave illusion, the results do not exclude the possibility that sequential interactions may be involved. One possibility is that the effect of sequential interactions depends on selective attention. Note that by having listeners attempt to segregate the illusion sequence by ear, Chambers et al had listeners attend analytically (Terhardt 1974; Houtsma and Fleuren 1991). The allocation of attention in this context may differ from that utilised by listeners in Deutsch's (1978, 1980, 1988) studies. In these experiments, listeners made a judgment on the percept, rather than a decision about the stimuli. Thus, listeners in Deutsch's studies may have been allocating attention synthetically; that is, to the overall percept rather than its constituent parts.

The present experiment was undertaken to determine the influence of attention on sequential interactions during the octave illusion. The effects of an analytic attentional strategy might manifest themselves in two ways. On the one hand, if analytic listening diminishes sequential interactions during the octave illusion, then a task that draws attention away from the eliciting sequence should increase sequential interactions. Alternatively, if the octave illusion depends on selective attention, then the prevention of analytic listening should *reduce* sequential interactions. These possibilities were explored in the present design by using the same measure of sequential interactions as that employed by Chambers et al (2002): the ability to perceptually segregate the final dichotic complex in an octave illusion sequence.

The task used to draw attention away from the illusion sequence (henceforth referred to as the load task) was to discriminate a brief noise burst containing a silent gap from a rapid stream of noise distractors. This task was undertaken simultaneously with presentation of the tonal sequence via headphones, and prior to the dichotic segregation task that listeners completed at the end of each tone sequence. In this way, attention was diverted from the eliciting sequence, but not from the stimulus that required dichotic segregation. To spatially separate the octave illusion and load task streams, the noise sequence was presented in free-field from a visible speaker.

To confirm that the load task was successful in drawing attention away from the octave illusion stream, participants were also instructed to respond to a probe stimulus embedded at a random position within the tonal sequence. Listeners therefore undertook three tasks on every trial: noise discrimination, probe detection in the illusion sequence, and dichotic segregation of the last stimulus in the illusion sequence.

Four variations of attentional load were blocked. In the no-load condition, both noise and probe detections were irrelevant and the only task was to segregate the final dichotic complex. This condition provided a baseline measure of dichotic segregation ability under conditions of full attention. In the probe-only condition, the noise sequence was irrelevant and listeners focused their attention entirely on detecting the probe, prior to the dichotic-segregation decision. In the low-load condition, both noise and probe tasks were relevant, with the noise stimulus relatively easy to discriminate from other stimuli in the noise sequence. Finally, in the high-load condition, participants again listened for both a noise and a probe target, but with the noise target relatively difficult to discriminate from other noises. In both the low-load and high-load conditions, noise discrimination was the primary task. Furthermore, listeners only monitored for probes prior to the execution of a noise response. This manipulation ensured that measures of probe detection indexed the effect of noise task difficulty. In this way, probe detection measures indicated the effect of attentional load on the capacity to monitor the octave illusion stream, prior to the dichotic-segregation decision that was used to assess the effect of sequential interactions on the octave illusion.

2 Method

2.1 *Participants*

Five right-handed listeners (three male, two female), aged 18 – 34 years, were paid for their participation.

2.2 *Apparatus and stimuli*

Octave illusion stimuli consisted of 400 Hz and 800 Hz tones, and were produced with identical parameters to those employed by Chambers et al (2002). These stimuli were presented for 200 ms over headphones at 70 dB SPL, with 5 ms rise/fall times, and separated by 200 ms silent intervals. Dichotic targets were generated with two frequency ratios: 2 : 1 (octave; experimental interval) and 4 : 1 (double octave; control interval). The octave interval was a dichotic chord of 400 Hz and 800 Hz tones; the double octave was a dichotic chord of 300 Hz and 1200 Hz tones. The auditory probe embedded within the octave illusion sequence was a 1347 Hz diotic pure tone of 180 ms duration, with a 5 ms rise/fall time. The frequency of the probe was selected on the basis of being inharmonically related to all other tones in the experiment. The probe could occur either between or simultaneous with successive dichotic octaves in the illusion sequence. When the probe was presented, it began 10 ms after the onset, and ended 10 ms before the offset, of either the dichotic octave or silent interval. The SPL of the probe was titrated separately for presentation between and within dichotic octaves through adaptive testing, as described below in section 2.3.

Noise stimuli were presented from a Pro-Beat model PB-16 speaker positioned directly in front of the listener at a distance of 57 cm. As shown in figure 2, the noise sequence contained four types of stimuli, each of 100 ms duration. All but three noises in every sequence were 20 – 20 000 Hz broadband noise bursts of 60 dB SPL, each with a 0.5 ms rise/fall time and with no silent interval between successive onsets (figure 2a). Each sequence also contained one high-load target, which was a noise burst of equivalent spectrum, duration, SPL, and rise/fall time, but with a silent gap inserted in the middle of the waveform (figure 2b). The duration of this gap was titrated to threshold levels through adaptive testing, as described in section 2.3. Each sequence

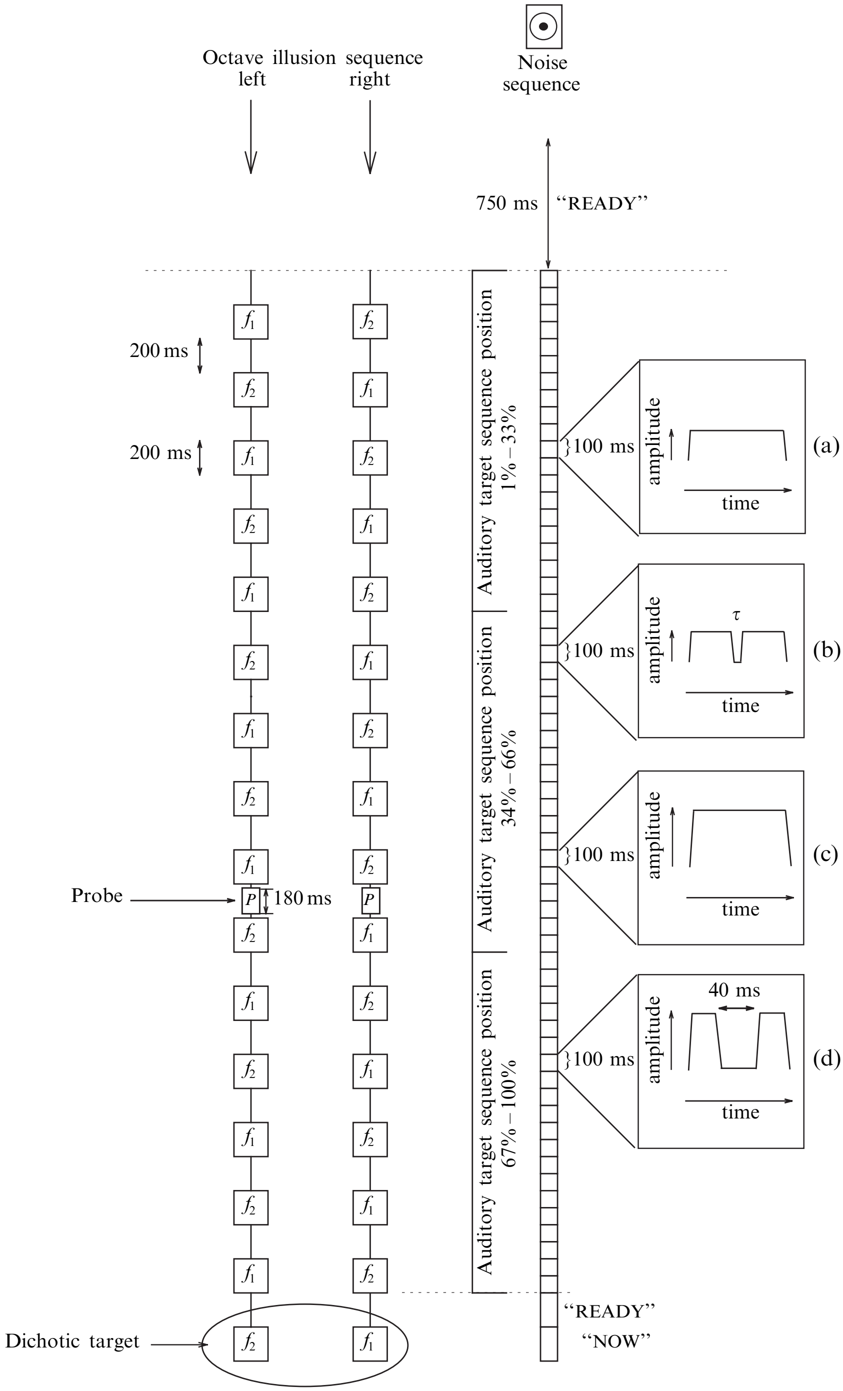

Figure 2. A schematic illustration of a typical trial. The auditory sequence length in this example is 16 tones, and the auditory target is a dichotic octave (circled). The labels f_1 and f_2 denote 400 Hz and 800 Hz tones, respectively, or vice versa, depending on the configuration of the first dichotic octave in the sequence. The four types of noise stimulus are shown in windows, including the high-load distractor (a), high-load target (b), low-load distractor (c), and low-load target (d). Each noise stimulus was presented for 100 ms, with the gap size of the quiet target (τ) titrated through adaptive testing, and the gap size of the loud target fixed at 40 ms. The probe was presented for 180 ms, and occurs in the above example between the ninth and tenth dichotic octaves.

also contained one low-load distractor, which was a 20 – 20 000 Hz noise burst of 75 dB SPL, 100 ms duration, 0.5 ms rise/fall time, and without a silent gap inserted in the waveform (figure 2c). The third type of noise stimulus was the low-load target, which was equivalent in spectrum, duration, SPL, and rise/fall time to the low-load distractor, but with a fixed gap of 40 ms duration inserted in the waveform (figure 2d). To prevent response interference between probes and noises, the onsets of the low-load target, high-load target, and probe in each sequence were separated by at least 1000 ms. The ordering of these three stimuli was counterbalanced across sequences, as was the ordering of the low-load target and low-load distractor, and the absolute sequence position of both low-load and high-load targets. A computer monitor displayed instructions and feedback to participants.

2.3 *Procedure*

All participants were tested individually in a sound attenuated chamber. The experiment was completed in two phases. In the first phase, detection thresholds for the diotic probe and high-load noise stimuli were obtained independently. Probe thresholds were measured in the absence of the noise stream. In this procedure, sequences of the octave illusion that were identical to those in the upcoming experimental blocks were presented in which one diotic probe was always embedded. Listeners responded as quickly as possible to the probe by pressing the left button of a two-button response box. The probe occurred randomly either between or simultaneous with any of the octave illusion stimuli. An initial probe SPL of 25 dB was decreased by 2 dB after three successive correct detections, and increased by 2 dB after every miss or false positive response (defined as a reaction time of <100 ms or >1000 ms). The threshold was calculated as the mean probe SPL of the final seven of nine reversals. This adaptive procedure converged approximately on the 79.4% correct point of the psychometric function (Levitt 1971). Simultaneous interleaved staircases were conducted for probes that occurred between or simultaneous with dichotic octaves. This procedure accounted for the simultaneous masking of probes by dichotic octaves, and was undertaken to ensure that all probes were of equivalent psychophysical discriminability. The probe SPL in the experimental blocks was set for each listener to the mean of five threshold estimates for each probe type.

Noise thresholds for the high-load target were measured in the presence of the octave illusion stimuli, but with probes omitted to ensure that noise threshold measurements would not be influenced by occasional shifts of attention to the probe. Listeners were instructed to focus all their attention on the noise stream and to respond as quickly as possible to the quiet noise with a gap by pressing the right button of a two-button response box as quickly as possible. Listeners were also told to refrain from responding to all other noises within the stream, including the several quiet noises without gaps (high-load distractors), the single loud noise without a gap (low-load distractor), and the single loud noise with a gap (low-load target). An initial noise gap duration of 15 ms was reduced by 0.5 ms after two successive correct detections and increased by 0.5 ms after every miss or false positive (as defined under the probe threshold procedure). The threshold was defined as the mean noise duration of the final seven of nine reversals, and estimated the 70.7% correct point of the psychometric function (Levitt 1971). Simultaneous interleaved staircases were conducted for noises that occurred between or simultaneous with dichotic octaves, to account for masking effects and to match the discriminability of all high-load targets. The high-load gap duration in the experimental blocks was set for each listener to the mean of five threshold measurements for each high-load noise type (simultaneous or interleaved). The gap for the low-load noise target was fixed across listeners at a suprathreshold duration of 40 ms.

In the second phase of testing, listeners were presented with simultaneous octave illusion and noise sequences, as shown in figure 2, and undertook the dichotic segregation task at the end of every sequence. Four load conditions were included in this phase. In the no-load condition, noise and probe stimuli were irrelevant and full attention was directed to the segregation task. In the probe-only condition, listeners were directed to ignore the noise stream and respond as quickly as possible to the probe with the left button (using their left hand). Listeners were instructed to monitor for the probe until they had made a response or until the word "READY" appeared on the computer display (whichever happened first), after which attention was to be directed to the segregation task. In the low-load condition, the primary task for listeners was to press the right button as quickly as possible with their right hand when a loud noise with a gap occurred. However, listeners were also instructed to respond as quickly as possible with the left button (using their left hand) to any probe that might occur prior to the execution of a noise response. In this way, a noise response, whether correct or incorrect, signified the need to shift attention to the segregation task. In the high-load condition, the speeded detection of the quiet noise with a gap was the primary task, again, with the accompanying secondary task of responding to any probe that might occur prior to the execution of a noise response. In both low-load and high-load conditions, if no noise response had been executed by visual presentation of the word "READY", listeners were instructed to shift to the segregation task.

To prevent the first dichotic stimulus in the octave illusion stream predicting the final dichotic target, the auditory sequence length was randomly set at either 15 or 16 tones, and the first dichotic octave was randomly set to 400-Hz – left, 800-Hz – right on half the trials and 800-Hz – left, 400-Hz – right on the remaining half. Steps were taken to ensure that the dichotic segregation judgment (executed with the same response box as the noise/probe detection) was not confused during data analysis with a probe or noise judgment. In the probe-only condition, if the only button-press during the trial occurred after presentation of the dichotic segregation response-prompt, listeners were further prompted afterward to report whether they had responded to the segregation task. If the answer was "no" (indicating a probe response), the trial was discarded and replaced. The same procedure was undertaken in low-load and high-load conditions if either no response, or only a probe response, had been executed by the time the segregation response-prompt was presented. In a separate phase of the study, subjective reports of the octave illusion were obtained from listeners for sequences of alternating dichotic octaves without probes and noises, and for sequences with probes and noises.

Prior to testing in the experimental phases, listeners completed 20 practice trials for the no-load and probe-only conditions, and a minimum of 40 practice trials for the low-load and high-load conditions. Feedback was provided for the probe and noise responses of practice trials, but not for the segregation judgment. Feedback was not provided for any aspect of the task in the experimental blocks. Each experimental session consisted of one combination of attentional load and dichotic response-prompt-type (ie which ear received the lower/higher pitch?). All sessions contained 4 blocks of 48 trials. Within each session, 32 trials were obtained for each combination of auditory target sequence position (ATSP) (1% – 33%, 34% – 66%, 67% – 100%) and dichotic target interval (octave, double octave), with the presentation order of harmonic interval and ATSP randomised within blocks. The order of load and dichotic response-prompt sessions was counterbalanced across listeners. Across all sessions, 64 trials per listener were obtained in each subcondition of attentional load, dichotic target interval, and ATSP, collapsed across dichotic segregation response-prompt-type. Participants completed the entire experiment over ten one-hour sessions; these included two threshold sessions (probe and noise) and eight experimental sessions (4 load conditions $\times$ 2 segregation response-prompt-type conditions).

3 Results

During presentation of the octave illusion sequence without probe and noise stimuli, all listeners reported a high pitch in the right ear alternating with a low pitch in the left ear. Crucially, subjective reports were unchanged by the addition of the noise stream and insertion of the probe stimulus with the octave illusion sequence.

Because the occurrence of a probe response in the present experiment was contingent on the execution of a noise response, the number of probe responses in the low-load and high-load conditions varied with the detectability of the noise, independently of attentional load. For example, because listeners only responded to the probe if a noise response had not yet been executed, fewer noise detections usually resulted in more probe responses. The proportion of correct probe responses was therefore adjusted to derive a measure of probe $p(c)$ independent of this contingency.[(1)] Reaction time (RT) analysis was unaffected by this procedure, with all correct probe RTs included within group means. Similarly, the proportion of correct probes in the probe-only condition remained unadjusted because probe responses in this condition were not contingent on the execution of a noise response.

The effect of noise task difficulty on probe detections is shown in figure 3, averaged across listeners. Figure 3a indicates the change in the proportion of detected probes and noises as a function of the auditory-attention condition. As expected from the titration procedures, listeners detected a greater proportion of low-load noise targets

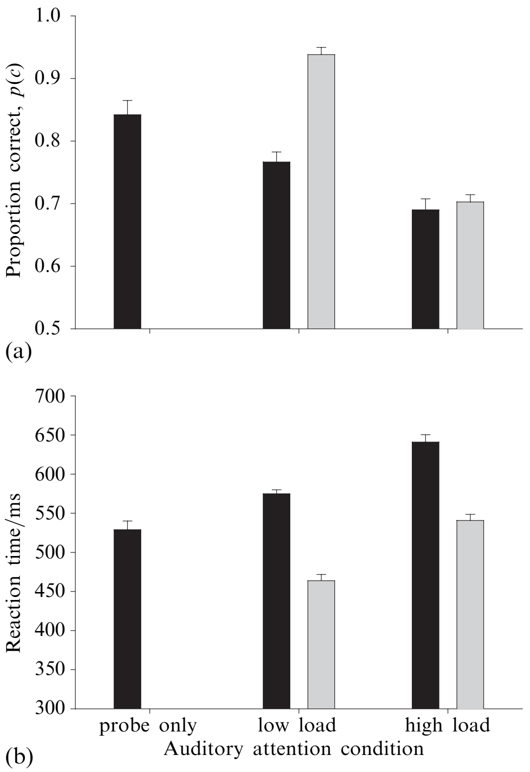

Figure 3. Attentional load results collapsed across all participants. Panel (a) indicates the proportion of correct detections for probe (black bar) and noise (grey bar) stimuli as a function of the auditory attention condition. Panel (b) shows the average correct reaction time for the same conditions. Error bars in both panels are +1 standard error of the mean.

[(1)] To calculate this adjustment, the total number of trials contributing to the denominator in the $p(c)$ probe equation was reduced depending on (i) the combination of probe and noise response types; (ii) the temporal order of the probe and noise; and (iii) the number of correctly detected noises. Three combinations of these conditions could lead to trial exclusion. The first two conditions arose when the noise preceded the probe, a noise response was made before the probe occurred (whether correct or incorrect), and no probe response was made. Because listeners were instructed to ignore probes that occurred after a noise response, the absence of a probe response than high-load noise targets ($t_4 = 10.2$, $p = 0.001$). It is also apparent from figure 3a that the proportion of detected probes decreased as the difficulty of the noise task increased, from no-load (0.84) to low-load (0.77) to high-load (0.69). A one-way ANOVA on probe detections confirmed a significant main effect of load ($F_{2,8} = 10.8$, $p = 0.005$, $\eta_p^2 = 0.73$).[(2)] Bonferroni comparisons indicated that listeners detected significantly more probes in the probe-only condition than in the high-load condition ($p = 0.046$), but not in the low-load condition compared to the high-load condition ($p > 0.1$).

Figure 3b shows the mean reaction time for correct detections as a function of load. Trends for increased probe and noise RT are apparent as the difficulty of the noise task was increased. A paired t-test confirmed that listeners responded faster to the low-load noise than the high-load noise ($t_4 = -4.8$, $p = 0.008$). A one-way ANOVA on the mean probe RT revealed a significant main effect of load ($F_{2,8} = 26.8$, $p = 0.001$, $\eta_p^2 = 0.87$, including Huyhn – Feldt correction). Bonferroni comparisons indicated that listeners responded significantly slower to probes in the high-load condition than in both low-load ($p = 0.009$) and probe-only ($p = 0.015$) conditions.

Dichotic segregation performance was analysed separately for trials in which the target in the auditory-attention condition was detected correctly, and for trials in which the target was missed. The $p(c)_{\max}$ coefficient was used to assess performance (Macmillan and Creelman 1991). This measure adjusts the raw $p(c)$ to control for lateral response bias, thus producing a sensitivity measure analogous to d'.[(3)] Figure 4 shows the average segregation performance for trials in which the auditory target was detected, collapsed across listeners and plotted as a function of the attentional load condition, harmonic interval, and ATSP. The serial position of the low-load noise target was included as the 'ATSP' factor in the no-load condition. The most notable trend in the results is the improved performance for double octave dichotic targets relative to octave targets. Furthermore, consistent with the results of Chambers et al (2002), listeners maintained performance significantly above chance at the octave interval across all load conditions (figure 4a; all $\chi_1^2 > 42.5$, all $p < 0.00001$). The results also exhibit some systematic influence of attention on performance, with a slight reduction in segregation performance as load was increased (figures 4b and 4c, particularly).

A three-way ANOVA was conducted on the mean segregation performance, including the within-subjects factors of attentional load (no-load, probe-only, low-load, high-load), harmonic interval (octave, double octave), and ATSP (1% – 33%, 34% – 66%, 67% – 100%). This analysis revealed a significant main effect of harmonic interval ($F_{1,4} = 8.0$, $p = 0.048$, $\eta_p^2 = 0.67$), but no main effect of attentional load ($F_{3,12} = 1.8$, $p > 0.2$, $\eta_p^2 = 0.31$; including Huyhn – Feldt correction) or ATSP ($F_{2,8} = 0.08$, $p > 0.8$, $\eta_p^2 = 0.02$; including Huyhn – Feldt correction). The interaction between attentional load and ATSP was almost significant ($F_{6,24} = 2.2$, $p = 0.077$, $\eta_p^2 = 0.36$), which may reflect the change in the direction of attentional effects between the ATSP 34% – 66% condition and the ATSP 67% – 100% condition, particularly at the octave interval. None of the other interactions approached statistical significance at $\alpha = 0.05$.

[(1)] (continued)
in this case cannot be interpreted as a 'miss'. These trials were therefore removed from the probe $p(c)$ denominator. The third condition arose when the noise followed the probe, a false positive noise response preceded the occurrence of the probe, and no probe response was made. Again, the absence of a probe response under this condition cannot be regarded as a miss because listeners would have ignored this probe, as instructed. The proportion of correct probe detections was calculated by dividing the number of correct probe detections by the adjusted denominator.

[(2)] The η_p^2 (partial eta-squared) coefficient is a measure of effect size, and is calculated as the proportion of the effect + error variance that is attributed to an effect $[\mathrm{SS}_{\mathrm{effect}}/(\mathrm{SS}_{\mathrm{effect}} + \mathrm{SS}_{\mathrm{error}})]$.

[(3)] The $p(c)_{\max}$ coefficient is calculated under a 2AFC design as $p(c)_{\max,\,2\mathrm{AFC}} = \Phi(d' \div \sqrt{2})$ where Φ is the cumulative normal distribution function.

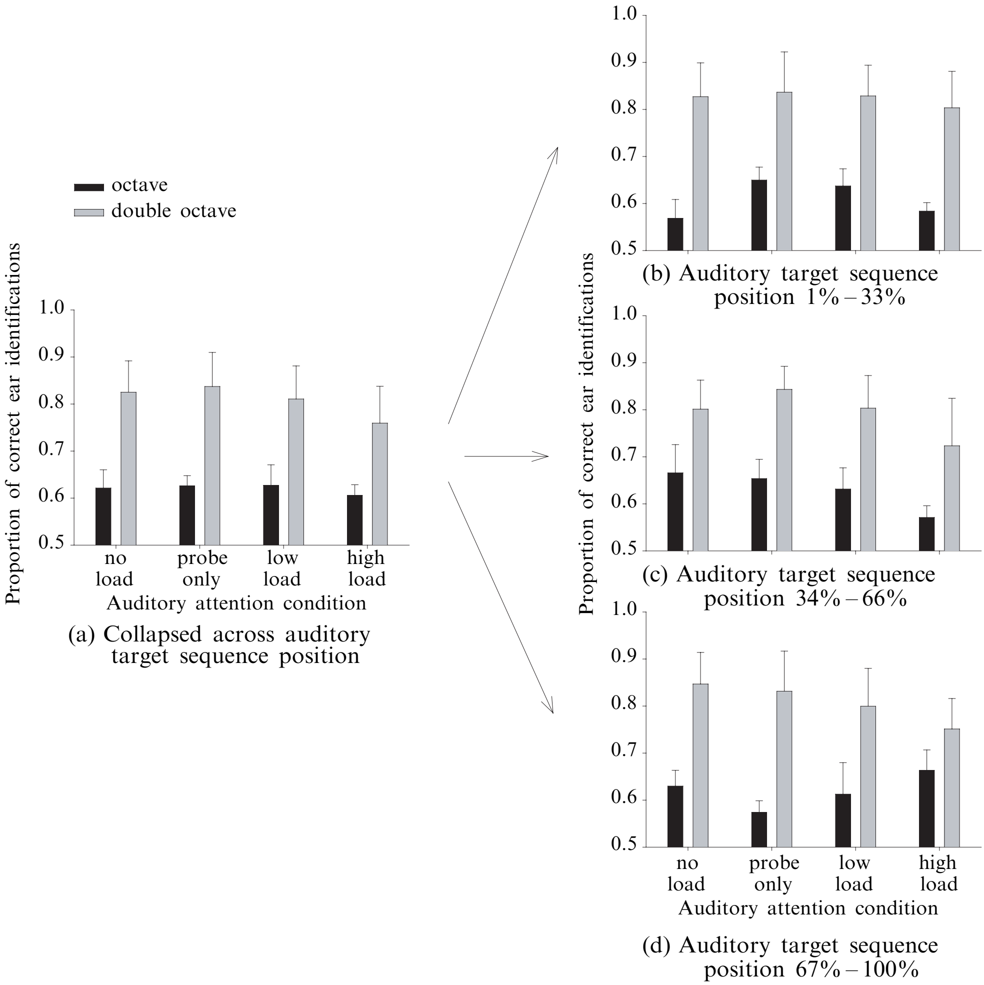

Figure 4. Average dichotic segregation performance for trials in which the auditory target was correctly detected. Results are collapsed across all participants and plotted as a function of attentional load, harmonic interval, and auditory target sequence position (ATSP). Panel (a) indicates the mean proportion of correct ear identifications for each combination of harmonic interval and attentional load, collapsed across ATSP. Panels (b), (c), and (d) show the results broken down into each ATSP subcondition. Error bars are +1 standard error of the mean.

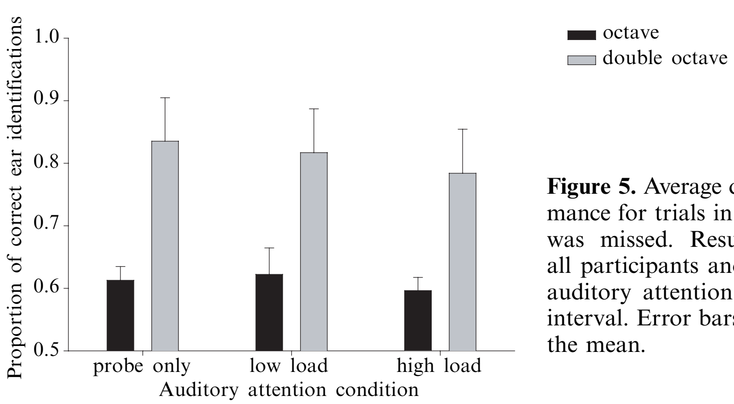

Figure 5. Average dichotic segregation performance for trials in which the auditory target was missed. Results are collapsed across all participants and plotted as a function of auditory attention condition and harmonic interval. Error bars are +1 standard error of the mean.

Segregation results for trials in which the auditory target was missed are shown in figure 5, collapsed across listeners. The only apparent trend in the results is the improved performance at the double-octave interval compared to the octave interval. A two-way ANOVA revealed a significant main effect of harmonic interval ($F_{1,4} = 8.5$, $p = 0.043$, $\eta_p^2 = 0.68$), but no main effect of attentional load ($F_{2,8} = 2.6$, $p > 0.1$, $\eta_p^2 = 0.39$), and no significant interaction between harmonic interval and attentional load ($F_{2,8} = 0.48$, $p > 0.5$, $\eta_p^2 = 0.11$).

4 Discussion

In this experiment we examined the effect of attention on sequential interactions in the octave illusion. Broadly, it was predicted that (a) if sequential interactions are instrumental in the octave illusion, and (b) if attention and sequential interactions are co-dependent, then manipulating the capacity to attend to the eliciting sequence should alter the octave illusion. Specifically, it was hypothesised that, if attention is necessary for sequential interactions, then removing attention from the eliciting sequence should reduce the effect of sequential interactions, thus enabling the final dichotic target in an illusion sequence to be more effectively segregated. Alternatively, if, by attending analytically, listeners are able to diminish the effect of sequential interactions, then removing attention from the eliciting sequence would be expected to increase the effect of sequential interactions. These predictions were proposed in the context of a recent study by Chambers et al (2002), which revealed no evidence that sequential interactions influence the octave illusion, but did not control for the possible effects of selective attention.

The results of this experiment support neither hypothesis and do not reveal any interaction between auditory attention and sequential interactions during the octave illusion. On average, listeners uniformly segregated the octave illusion significantly above chance, irrespective of the attentional load, position of the auditory target in the noise sequence, or whether the noise target was detected or missed. These findings are consistent with evidence reported by Chambers et al (2002), and suggest that the null effect obtained in this earlier study was unlikely to have arisen owing to the uncontrolled influences of attention and analytic listening.

As noted in section 1, the suppression model proposed by Deutsch and Roll (1976) depends critically on the effects of sequential interactions to explain theoretical inconsistencies with past literature on pitch perception and ear dominance. Specifically, the theory requires that sequential interactions (a) enable suppression to supercede the harmonic fusion of dichotic complex tones; and (b) strengthen ear dominance to the extent that only the frequencies in one ear are perceived. The apparent null influence of attention on this hypothesised mechanism, combined with evidence against sequential interactions per se (Chambers et al 2002), thus challenges the general validity of the suppression model.

In contrast to the explanation provided above, there are four possible alternative explanations for the null effect of attention in the present study. First, it is possible that the presentation of simultaneous noises and insertion of probes in the eliciting sequence degraded the illusion. Note, however, that subjective reports of the illusion were consistent with standard observations (eg Deutsch 1974, 1983), whether these extra stimuli were present or absent from the eliciting sequence. Therefore, even if the illusion was subtly degraded, it was certainly not eradicated. Second, it might be argued that the null result reflects a floor effect of performance at the octave interval. We suggest that this possibility is also unlikely because listeners segregated dichotic octaves significantly above chance during the octave illusion (see black bars in figure 4). Third, might it be argued that sequential interactions and auditory grouping occur pre-attentively, and are thus immune to the attentional manipulation in this experiment?

(see Kubovy and Van Valkenburg 2001 for discussion). On the basis of evidence presented by Carlyon et al (2001), we suggest that this possibility is unlikely. They showed that auditory streaming in one ear is reduced when listeners perform a demanding attentional task in the other ear, indicating that auditory grouping and attention are interdependent. A fourth possibility is that our manipulation of attentional load may have been ineffective. Note that the difference in noise detection performance between low-load and high-load conditions cannot be used to draw conclusions about attention because the target stimuli themselves differed (Pashler 1998). The relationship between probe detection and noise task difficulty, however, allowed an objective verification of attentional load, because the probe stimulus was identical in all blocks; thus changes in *probe* detection must have reflected modulation by selective attention rather than changes in received sensory information. The analysis of probe detections suggested that the attentional manipulation was successful because listeners detected significantly fewer probes, and responded significantly slower to probes, that were accompanied by the high-load noise task (see figure 3). Despite the success of the attentional manipulation, however, it might be argued that the magnitude of load differed insufficiently between the low-load and high-load conditions to reveal an effect on sequential interactions. We suggest that this possibility is also unlikely because segregation performance did not differ between the no-load condition and the low-load or high-load conditions, nor between the probe-only condition and the load conditions. Since the attentional cost of the high-load condition relative to the probe-only condition was substantial [a $p(c)$ reduction of ~ 0.15 and RT increase of $\sim$150 ms], an effect of attention, if present, would be expected to manifest itself between these extremes of attention allocation. As this finding was not observed, the results imply the true absence of an attentional influence rather than an insensitivity of the attentional manipulation.

Taken together, previous results obtained by Chambers et al (2002), in addition to the present findings, raise significant doubts about the suppression model of the octave illusion. In addition, this research suggests that the remarkable capacity of listeners to segregate the octave illusion is affected neither by prior sequential presentation, nor by the allocation of selective attention to the preceding sequence. It is possible, of course, that a measure of the octave illusion other than dichotic segregation may be influenced by both sequential interactions and selective attention. However, other than dichotic segregation, an objective, psychophysical measure of sequential interactions is not readily conceivable. On the basis of current evidence, sequential interactions do not appear to be an important factor in the perception of the octave illusion.

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