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Perceived intensity effects in the octave illusion

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We showed that there is an intensity aspect to the octave illusion in addition to the pitch and location aspects originally reported by Deutsch (1974). In Experiment 1, we asked participants to directly compare the stimulus giving rise to the illusion (ILLU) with one mimicking its most commonly reported percept (illusion consistent; IC) and showed that they were easily able to distinguish between the two. In Experiment 2, we demonstrated a clear difference between the perceived loudness of ILLU and IC when IC follows ILLU, but not when IC precedes ILLU. In Experiments 3 and 4, we showed that this effect depends on the alternation of high and low tones between the ears in an extended pattern. In Experiment 5, we showed that this difference in perceived loudness disappears if the interval between the ILLU and IC stimuli is sufficiently large.

Complex sounds contain energy at a number of different frequencies. In a typical environment, several objects emit complex sounds overlapping in time. The inner ear performs a frequency analysis over time on the sum of these incoming sound waves, leaving it to higher stages of processing to appropriately recombine the various components into an accurate representation of the original environment. In order to do this, the auditory system must determine *what* the auditory objects are and *where* they are located in space.

One of the first researchers to study the interaction between the auditory *what* and *where* pathways was Deutsch (1974), who demonstrated an interesting phenomenon that she termed the "octave illusion." When participants were presented with an alternating sequence of high (800-Hz) and low (400-Hz) pure tones (such that tones were presented to both ears simultaneously but out of phase, so the left ear was receiving the low tone while the right ear was receiving the high tone, and vice versa), most reported hearing a high tone in the right ear followed by a low tone in the left (see Figures 1A and 1B). When the headphones were reversed so that the left headphone now presented tones to the right ear and the right headphone presented tones to the left, most listeners reported the same percept: The high tone was still heard in the right ear. Most right-handed participants heard the illusion in this manner, but left-handed participants were just as likely to localize the high tone in the left ear as in the right. Deutsch (1983) suggested that this difference might be due to hemispheric dominance, with the high tones perceived as coming from the dominant ear.

The octave illusion presents a paradox. Although each ear receives a sequence of high and low tones (see Figures 1A and 1B), Deutsch found that the most commonly reported percept was an alternating pattern with the high tones heard as though they were being presented solely to one ear and the low tones as though they were being presented solely to the other. Interestingly, the low tone is perceived as coming from the ear that is actually being presented with the high tone at that time. In the interpretations of the octave illusion offered by Deutsch and colleagues (e.g., Deutsch, 1975, 1983; Deutsch & Roll, 1976), the location (where) information is determined solely by the higher pitched tone, and information from the lower tone is discarded. The pitch (what) information is determined solely by the input to the dominant ear, and information from the nondominant ear appears to be discarded (but see Chambers, Mattingley, & Moss, 2002, 2004, for an alternative, fusion-based model). However, research to date on the octave illusion has been based primarily on verbal reports or methods that do not attempt to quantify the percept across all acoustic dimensions, so it remains unclear whether information from one ear is completely suppressed or whether it makes some contribution to the perceived pitch, timbre, location, and/or intensity of what is heard. We explore this issue in Experiment 1.

More recently, researchers have turned to functional imaging techniques in an attempt to untangle the perceptual mechanisms underlying the octave illusion. Lamminmaki and Hari (2000) conducted a study using magnetoencephalography (MEG) and suggested that the location of the N100m component of the auditory evoked field corresponds to the perceived locations of the tones elicited by the illusory stimulus rather than their actual locations. However, there is debate in the literature about both the generators and the functional significance of the N100m component(s).

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A Illusion-Eliciting Stimulus

Right	**H**	L	**H**	L	**H**
Left	L	**H**	L	**H**	L

B Most Commonly Reported Percept

Right	**H**	–	**H**	–	**H**
Left	–	L	–	L	–

C Illusion-Consistent Occasional Stimulus

Right	**H**	L	**H**	–	**H**
Left	L	**H**	–	L	L

D Illusion-Deviant Occasional Stimulus

Right	**H**	L	–	L	**H**
Left	L	**H**	**H**	–	L

Figure 1. (A) The octave illusion-eliciting stimulus. (B) The most commonly reported percept. (C) The octave illusion stimulus containing occasional illusion-consistent changes (shown in the highlighted box) from Ross, Tervaniemi, and Näätänen (1996). (D) The octave illusion stimulus containing occasional illusion-deviant changes (shown in the highlighted box) from Ross et al. High tones (H) are 800-Hz, 250 d low tones (L) are 400-Hz, 250-msec pure tones.

Ross, Tervaniemi, and Näätänen (1996) conducted an electroencephalographic study using mismatch negativity (MMN) in an oddball paradigm to investigate where in the auditory system the illusion was being created. MMN is thought to represent an index of discrimination in the auditory cortex and is seen in the electrophysiological response when an occasional change is introduced in a repeating auditory stimulus (see Picton, Alain, Otten, Ritter, & Achim, 2000, for a detailed review of MMN). Ross et al. presented a stimulus based on Deutsch's (1974) illusion-eliciting stimulus on 95% of trials. On 2.5% of trials, an illusion-consistent deviant (IC; the "most commonly" reported percept from Deutsch, 1974) was presented, which was assumed to be indistinguishable from the octave illusion stimulus; on the remaining 2.5% of trials, an illusion-inconsistent deviant was presented, which was assumed to be easily distinguishable from the octave illusion stimulus (see Figures 1C and 1D). Ross et al. reported that both deviant events elicited MMN. This MMN was found in a position suggesting that its principal generator was the primary auditory cortex, and Ross et al. interpreted this to imply that "at the level of pre-attentive processing there are different representations for two stimulus categories which are identically perceived in terms of pitch and lateralization" (p. 304). In other words, they argued that at a preattentive stage of processing, the octave illusion stimulus and the stimulus corresponding to its most commonly reported percept are clearly distinguished. Since the MMN was found to be similar for both of the deviant stimuli, Ross et al. further suggested that the auditory system creates the illusion from the stimuli beyond the level of the primary auditory cortex. This hypothesis is consistent with the notion that the illusion is based on competition between different regions of perceived auditory space rather than direct competition between auditory input from one ear and the other (e.g., Deutsch, 1980, 1983; Deutsch & Roll, 1976).

An alternative explanation of Ross et al.'s (1996) findings is also possible, however. They did not report testing whether the so-called illusion-consistent stimulus was actually perceived identically to the illusion-eliciting stimulus. If not, the MMN could have been generated simply because the deviant stimuli sounded different in some way from the standard stimuli. If the illusory and illusion-consistent stimuli are in fact perceived to be different, the single tones that participants report hearing are some combination of the two tones that are presented simultaneously: In other words, the "unheard" tone is influencing the loudness, timbre, or location of the "heard" tone. In Experiment 1, we asked participants to directly compare their percepts of the illusion-eliciting stimulus and the illusion-consistent stimulus used by Ross et al. In Experiments 2, 3, 4, and 5, we further investigated perceptual differences between the illusory and illusion-consistent stimuli and found that the illusion has an intensity component that is specific to the illusory stimulus, in addition to the pitch and location components previously reported (e.g., Deutsch, 1974).

EXPERIMENT 1

Method

Participants. Eighteen psychology students (9 male, 9 female) from 19 to 35 years of age (*M* = 22.5) participated. All but one were right-handed. Questionnaires revealed that the participants had from 0 to 18 years of formal musical training, with a mean of 5.5 years. Using handedness questionnaires, laterality quotient (LQ) scores were calculated as suggested by Oldfield (1971). Right-handed participants had a mean LQ score of +82, decile R.6 (LQ range = 50–100, decile range = R.2–R.10), which is a typical distribution of scores for right-handed participants. The left-handed participant had an LQ score of −30, decile L.2. The data from the left-handed participant were included in all analyses since his results were consistent with those of the right-handed participants. None reported any hearing problems.

Apparatus and Stimuli. The stimuli were generated using a KYMA sound design workstation. Four monaural pure tones were generated, at frequencies of 400 and 800 Hz. Two dichotic complex tones were also created. The first consisted of a 400-Hz tone presented to the left ear and an 800-Hz tone presented simultaneously to the right ear; in the second, the ears were reversed. All tones were 250 msec in duration, including 5-msec linear attack and decay envelopes. It should be noted that Deutsch's (1974) original stimuli did not use attack and decay envelopes. However, subsequent studies (e.g., Akerboom, ten Hoopen, & van der Knoop, 1985) have shown the illusion to be robust in the face of both attack and decay envelopes, and also with silent intervals inserted between the tones.

The tones were arranged into sequences to create five stimuli, each comprising 20 tones and lasting 5 sec (see Figure 2). The first stimulus was the illusion-eliciting (ILLU) stimulus, which was a replica of Deutsch's (1974) stimulus, in which the two dichotic complex tones alternated. The second and third stimuli were both illusion consistent (IC): The sequences presented were the same as those that most of Deutsch's participants reported hearing when presented with the ILLU stimulus (i.e., a repeating pattern of low tones in one ear alternating with high tones in the other ear). The high tones were presented in the right ear in one stimulus (IC–RH) and in the left ear in the other (IC–LH).[1] The remaining two stimuli were illusion-deviant (ID), constructed with the tones in random order such that the high tones were all presented in the right ear (ID–RH) or the left ear (ID–LH). The ID stimuli were used as a control condition, since they should be clearly distinguishable from both the IC and ILLU stimuli.

The experiment was run on an Apple Macintosh IIci computer, using custom in-house software. Participant responses were made using a button-box interface, and responses were recorded on line for later evaluation. The stimuli were presented using Telephonics TDH49P audiological headphones that were connected to the computer via an AudioMedia sound card and Denon PMA 480R amplifier. The experiment was conducted in an Industrial Acoustics sound-attenuating chamber with a background noise level of less than 24 dB(A). The stimuli were all presented at a peak SPL of 65 dB(A) at each ear.

Procedure. The experiment consisted of four phases: stimulus description, training, testing, and control. Participation in the testing and control phases was conditional on a predetermined performance level in the training phase.

In the stimulus description phase, the participants were presented with the ILLU stimulus and were asked to describe in as much detail as possible what they heard. The participants were then given a set of instructions outlining the experimental procedure. Once they had indicated that they understood the instructions, the training phase of the experiment began.

The training, testing, and control phases of the experiment all followed the same general procedure. On each trial, two stimuli were presented. First, the participants heard one of the stimuli shown in Figure 2 and were asked to decide from which ear the higher of the tones was coming, making their response with the but-

ILLU (Deutsch's octave illusion stimulus)

Right	**H**	L	**H**	L	**H**	L	**H**	L	**H**	L
Left	L	**H**	L	**H**	L	**H**	L	**H**	L	**H**

IC–RH (most commonly reported percept)

Right	**H**	–	**H**	–	**H**	–	**H**	–	**H**	–
Left	–	L	–	L	–	L	–	L	–	L

IC–LH (less commonly reported percept)

Right	–	L	–	L	–	L	–	L	–	L
Left	**H**	–	**H**	–	**H**	–	**H**	–	**H**	–

ID–RH (randomly generated)

Right	**H**	–	**H**	**H**	–	**H**	–	–	**H**	–
Left	–	L	–	–	L	–	L	L	–	L

ID–LH (randomly generated)

Right	–	L	L	–	–	L	–	L	–	–
Left	**H**	–	–	**H**	**H**	–	**H**	–	**H**	**H**

Figure 2. The stimuli from Experiment 1. High tones (H) are 800-Hz, 250-msec pure tones, and low tones (L) are 400-Hz, 250-msec pure tones. ILLU, illusion eliciting; IC, illusion consistent; ID, illusion deviant; RH, high tones on the right; LH, high tones on the left.

ton box. The participants were then presented with another stimulus from Figure 2 and asked to decide whether the second stimulus was identical to, or different in some way from, the first stimulus, again indicating their responses via the button box. The participants also indicated when they were ready for the next trial to begin via the button box.

The purpose of the training phase was to ensure that the participants were familiar with the operation of the button box and the tasks required of them and that they were able to discriminate between the different control stimuli. The first trial consisted of the IC–RH stimulus, followed again by the IC–RH stimulus. This trial was repeated up to a maximum of 10 times until the participants responded correctly ("right," followed by "same"). If the participants did not respond correctly by this time, training was aborted, and the experiment was terminated. The next trial consisted of IC–LH followed by IC–RH, and the participants again had 10 trials to respond correctly ("left," followed by "different") before training was aborted. The remaining trials in the training phase were randomized to consist of one of the IC stimuli followed by another of the IC stimuli, and the participants were required to respond correctly to five trials in a row. If they did not do so within 20 trials, training was aborted, and the experiment was terminated. Upon successful completion of the training phase, they proceeded to the testing phase.

Every trial of the testing phase began with the ILLU stimulus. The second stimulus presented was ILLU, IC, or ID. Whether the high note was presented on the left or right in the second stimulus depended on which ear the participants indicated the high notes had come from in the first stimulus (ILLU). If they indicated that the high notes were in the right ear, they were given ILLU, IC–RH, or ID–RH; if they indicated the left ear, they were given ILLU, IC–LH, or ID–LH. Fifty percent of trials had ILLU as the second stimulus, 25% had IC, and 25% had ID. Thirty-two trials were presented during this phase, in randomized order such that no more than 2 consecutive trials were identical.

Upon completion of the testing phase, the participants automatically proceeded to the control phase, whose purpose was to ensure, first, that the participants were still concentrating, and second, that they were able to discriminate between stimuli whose high notes were on the same side but whose pitches were in different orders. Every trial of the control phase began with the IC stimulus. Fifty percent of the trials started with IC–RH, and 50% with IC–LH. The second stimulus in each trial was IC–RH, IC–LH, ID–RH, or ID–LH, each occurring in 25% of the trials. Again, 32 trials were presented during this phase, and all were randomized such that no more than 2 identical trials could follow each other and that exactly 8 trials should have elicited a "same" response.

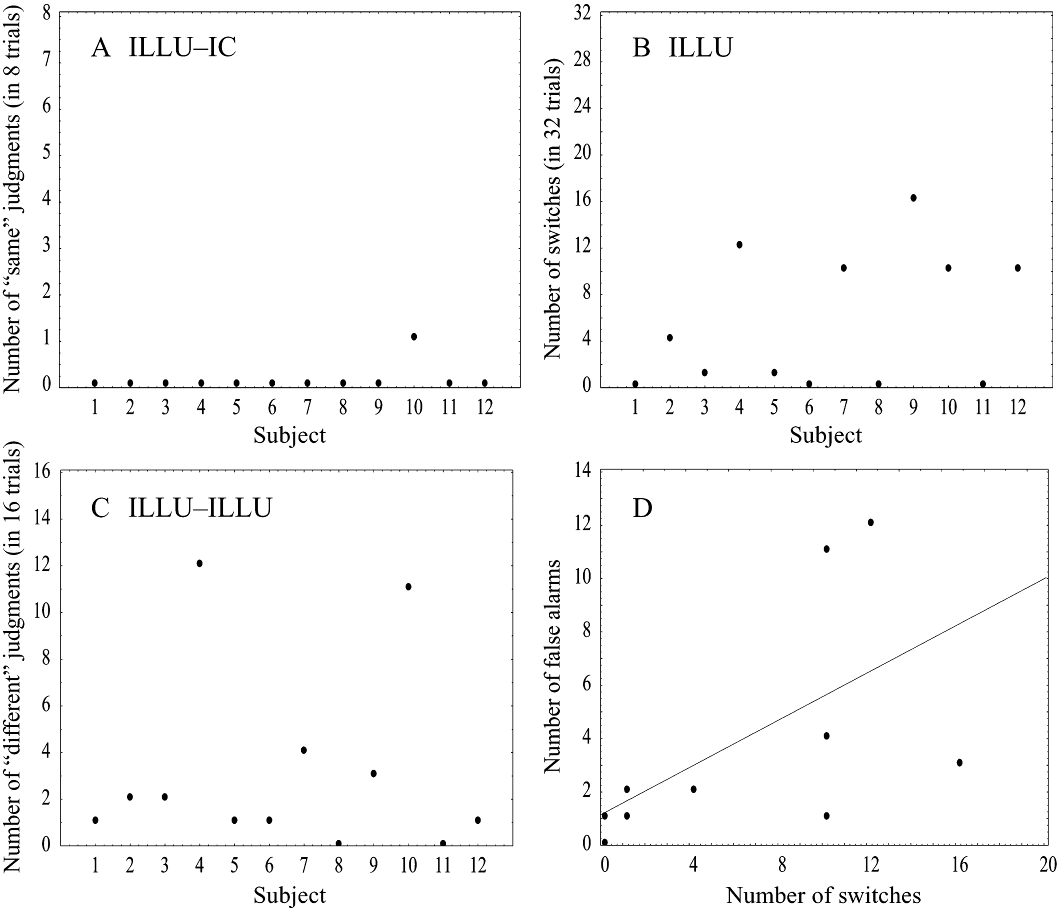

Figure 3. The results from Experiment 1. (A) ILLU and IC were almost always judged as different. (B) There was large variability in participants' perception of the ILLU stimulus. Some heard the high note switch sides frequently, and others did not. (C) There was also high variability in the number of times the ILLU stimulus was judged as different when it immediately followed an identical ILLU stimulus. (D) There was a significant correlation between the number of times the high note switched sides and the number of times the ILLU stimulus followed by the ILLU stimulus was judged as different.

Results and Discussion

Three participants failed to pass the training phase of the experiment and were excluded from subsequent phases. Three additional participants had false alarm rates of 25% or more for the control trials and were also excluded from the data analysis. The remaining 12 participants indicated that they heard the ILLU stimulus in a manner consistent with Deutsch's (1974) original observations (i.e., a series of alternating tones with the high notes in one ear and the low notes in the other ear). However, in the testing phase these participants indicated that the ILLU and IC stimuli sounded identical on only 1% of trials (1 out of 96; see Figure 3A). These results clearly indicate perceptual differences between the ILLU and IC stimuli when they are directly compared. These differences may be in the timbre, intensity, exact pitch, or exact location of the perceived tones.

It is interesting to note the amount of variation between participants in their perception of the ILLU stimulus. Fifty percent of participants (6) who passed training heard the stimulus in a very consistent manner, with the higher tone switching sides between presentations no more than once during the 32 trials, whereas 41% of participants (5) seemed to hear it in a very unstable fashion, with the higher tone switching sides between presentations more than nine times during the 32 trials (see Figure 3B).[2] Verbal reports also indicated that for some participants, the higher tone may have switched sides within the course of a single presentation, although this was not directly tested. When the ILLU stimulus was followed by the ILLU stimulus, participants responded "different" on 20% of trials, whereas when the IC stimulus was followed by the IC stimulus again, participants only responded "different" on 6% of trials. The false alarms for the ILLU–ILLU trials were not distributed equally across all participants (see Figure 3C): The 6 participants who reported the higher tone switching sides no more than once had a similar false alarm rate for both the ILLU–ILLU (5.2%) and IC–IC (4.1%) trials, whereas the 5 participants who reported the higher tone switching sides more than nine times had a much higher false alarm rate for the ILLU–ILLU trials (38.8%) than for the IC–IC trials (7.5%). If the higher tone is heard on different sides for different presentations of the ILLU stimulus, a high false alarm rate on ILLU–ILLU trials would be predicted for participants who reported the higher tone to be switching sides frequently. This prediction is supported by the data: Spearman rank correlation analysis revealed a significant correlation between the number of times the higher tone was perceived to switch sides and the number of false alarms ($r_s = .82$, $n = 12$, $p = .002$; see Figure 3D).

Brennan and Stevens (2002) reported that expert organists, who were familiar with sounds similar to the illusory stimulus, were more likely to hear the illusion veridically. We performed correlational analyses to examine the effects of musical experience (both listening and playing) and handedness on the side on which the higher tone was perceived, the number of times the high tone switched sides, and the number of false alarms, but no significant effects were found, possibly because our participants did not have a wide enough range of experience or handedness.

Ross et al. (1996) reported that MMN was found for both illusion-consistent and illusion-inconsistent stimuli when they were occasionally interleaved with a repeating pattern mimicking the percept elicited by the ILLU stimulus. They concluded that "two categories of auditory stimuli which have different spectral structure but which are identically perceived in terms of pitch and lateralization are differently encoded at the level of sensory memory. This implies that the octave illusion is created by the central nervous system beyond the level of the auditory cortex" (p. 305). However, no behavioral measures were reported by Ross et al., aside from asking participants to describe their perception of the illusory stimulus prior to the event-related potential (ERP) study, so what participants perceived is not entirely certain. Experiment 1 has shown that the illusory and illusion-consistent stimuli used by Ross et al. were probably not perceived as identical. The nature of the differences is as yet unclear, but given that participants were reliably able to judge the IC stimulus as different from the ILLU stimulus, the fact that MMN was elicited is not remarkable. It could be that the illusion-consistent stimulus was simply perceived as different from the illusory stimulus, and this perceptual difference would generate MMN (Näätänen, 1992; Picton et al., 2000). It might be expected that the MMN elicited by the illusion-consistent stimulus would be smaller than that elicited by the illusion-inconsistent stimulus, but this is not the case in the results presented by Ross et al. It is possible that both of these stimuli may have been perceived as sufficiently different from the illusory stimulus that a ceiling was reached in terms of the MMN that was elicited. Another possibility, given the pattern of the data from the present study, is that some participants may have switched the ear in which the higher tone was heard during the experiment. This would mean that the illusion- consistent stimulus was in fact no longer consistent at all, resulting in little, if any, perceived difference between the illusion-consistent and illusion-inconsistent deviant stimuli used by Ross et al.

Experiment 1 showed that the illusion does not result from simply discarding the information from one ear. Several studies have shown that the illusion is often heard in an unstable manner (e.g., Deutsch, 1974, 1975, 1980, 1983). Experiment 1 showed that some participants report frequent switches in the ear hearing the higher tones on successive presentations of the illusion-eliciting stimulus. As mentioned previously, there might be differences in pitch, timbre, location, or intensity when the illusory stimulus is directly compared with an illusion-consistent stimulus, even though a simple verbal report of the percept of the illusory stimulus might not reveal such differences. Although no participants could clearly identify how they were able to distinguish between the stimuli (comments such as "they were just different" were not uncommon), the present study offers clear evidence that they are perceptually distinct.

It seems likely that the dichotic[3] ILLU stimulus (which stimulates the two ears simultaneously, with different signals being presented to each ear) might sound louder than the diotic IC stimulus (which stimulates just one ear at a time) as a result of binaural loudness summation. Reynolds and Stevens (1960) showed that across a wide range of frequencies, a pure tone presented to two ears simultaneously was judged to be between 3 and 10 dB louder than a pure tone presented to just one ear, depending on the absolute level of presentation (the higher the level of presentation, the larger the difference). Several other researchers have reported similar results, even when the tone presented to each ear differs in frequency by an octave or more (e.g., Hellman & Zwislocki, 1963; Marks, 1978, 1980; Scharf & Fishkin, 1970). In Experiment 2, we investigated whether there are intensity differences in the percepts elicited by the ILLU and IC stimuli.

EXPERIMENT 2

Method

Participants. Fifty-four psychology students (8 male, 46 female) from 19 to 66 years of age ($M = 22.6$) participated in this experiment for course credit. Forty-eight were right-handed. All the participants completed questionnaires concerning musical experience and handedness, as in the previous experiment. None reported any known hearing loss.

Apparatus and Stimuli. The sound generation equipment and sound-attenuating chamber were identical to those of Experiment 1. The experiment was run on an Apple Macintosh 7123/80 computer. The IC and ILLU stimuli from Experiment 1 were used.

Intensity scaling of the stimuli was done on line according to an adaptation of the PEST procedure (Pollack, 1968; Taylor & Creelman, 1967), using custom software. Intensities ranged from 40 to 75 dB(A), and stimuli were presented over a background noise floor of less than 24 dB(A).

Procedure. The experiment consisted of three phases: screening, testing, and replication. Participation in the testing and replication phases was conditional on a predetermined performance level in the screening phase. The replication phase took place on a separate visit.

During screening, the participants were presented with the ILLU stimulus and were asked from which ear they perceived the higher tone to be coming, responding via the button box. Next, they were presented with the IC–RH stimulus and asked the same question. They were then presented with a randomized order of the ILLU (eight trials), IC–RH (four trials), and IC–LH (four trials) stimuli and asked to make the same judgment as to whether the higher tone was heard in the left or right ear. The participants who responded differently to more than three of the ILLU stimuli were excluded from the rest of the study on the grounds that they did not hear the illusion in a stable manner, so we could not be sure exactly what they were hearing on any trial. Furthermore, the participants who responded "left" on three or more ILLU trials or made more than three errors on the IC trials were excluded from the study, since we wanted to use only those participants who were paying attention, were able to use the button box appropriately, and perceived the ILLU stimulus in the manner reported as most common by Deutsch (e.g., Deutsch, 1974). The participants who responded consistently and met these criteria proceeded straight to the testing phase.

Each trial in the testing phase followed the same general procedure. The participants were presented with one stimulus followed by a 500-msec period of silence, and then another stimulus. They were then asked to decide whether the first or second stimulus was louder, responding via the button box. The first stimulus was always presented at a fixed level (60 dB[A]); the level of the second stimulus was altered according to the PEST procedure (Pollack, 1968; Taylor & Creelman, 1967), which enables thresholds to be found and verified in a relatively small number of trials. The experiment terminated when the step size reached a predefined limit (0.1 dB, based on pilot studies), or after 40 trials, whichever occurred first. Data from the participants who did not reach threshold after 40 trials were excluded from the analysis. The threshold at which the participants perceived the first and second stimuli as being of equal loudness was then calculated by taking the average of the last four reversal points. In order to ensure that the experiment did not terminate before the participants were close to their threshold, a minimum of 24 trials was forced.

To control for order effects, three conditions were run concurrently (i.e., with trials interleaved) in the testing phase. The first (IC–IC) had the IC–RH stimulus as both the first and second stimuli. The second (IC–IL) had the IC–RH stimulus as the first stimulus and the ILLU stimulus as the second. The third (IL–IC) had the ILLU stimulus as the first and the IC–RH stimulus as the second. Each participant was initially presented with six trials of the IC–IC condition, and thereafter, trials were randomly selected across all three conditions such that no more than three consecutive trials came from the same condition until this was no longer possible (due to conditions not terminating at the same time). The initial trials for each condition started with an intensity difference of 6 dB. Whether this was a positive or negative difference was determined by chance; in fact, approximately 55% of trials started with a negative difference. Upon completion of the experimental phase of the experiment, the participants arranged a time to return for the replication session (from 7 to 14 days later).

The primary purpose of the replication phase was to show that the results from the experimental phase were repeatable. Most participants were run through the "repeat" replication that used a procedure identical to that used in the experimental phase. A few participants were run through the "long" replication, which was identical to the original procedure, except with a greater number of trials (a minimum of 40 and a maximum of 60) in order to verify that we were allowing enough trials to accurately estimate the threshold. Finally, in order to ensure that an apparent perceptual asymmetry in the results of the initial experiment was not caused by a programming error, a few participants were run through the "reverse" replication, in which a few lines in the code were reversed, such that the IC–IL condition actually resulted in the participants being presented with the IL–IC condition, and vice versa. The participants were assigned to these replications at random, so that 2/3 were run in the repeat replication, 1/6 in the long replication, and 1/6 in the reverse replication.

Results and Discussion

Of the 54 participants who signed up for this experiment, 26 failed to pass the initial screening and were excluded from the rest of the study. This proportion of participants was consistent with the results from Experiment 1. Of the remaining 28 participants, 14 ran in the repeat replication, 5 ran in the long replication, and 4 ran in the reverse replication. Five participants did not return for the replication phase.

In each experimental condition, the average of the last four reversal points (according to the PEST procedure outlined previously) was calculated for each participant. This enabled us to estimate a level at which the second stimulus would have to be presented in order for the two stimuli to be judged "of equal loudness" (see Pollack, 1968). The statistical analysis was then performed on these calculated means.

For each participant, in each condition, the difference in intensity between the two stimuli when they were judged to be equally loud was determined. For the control condition (IC–IC), the mean score was −0.13 dB ($n = 28$, $SD = 0.38$), which was not significantly different from 0 when tested using a single-sample t test. For the IC–IL condition, the mean score was 0.75 dB ($n = 28$, $SD = 2.05$), which was also not significantly different from 0. However, for the IL–IC condition, the mean score was −7.66 dB ($n = 26$, $SD = 8.20$), which was significantly different from 0 [$t(25) = -4.766$, $p < .001$]. (Two participants did not complete this condition before the maximum number of trials was reached, so it was not possible to obtain their thresholds.) For each of the replications (repeat, long, and reverse), participants' results in each replication type were compared with their results in the experimental phase. In each case, two-tailed, paired-sample t tests showed that for all three conditions (IC–IC, IC–IL, and IL–IC), there were no significant differences between the scores from the experimental phase and the corresponding scores from the replication phase (see Figure 4A).

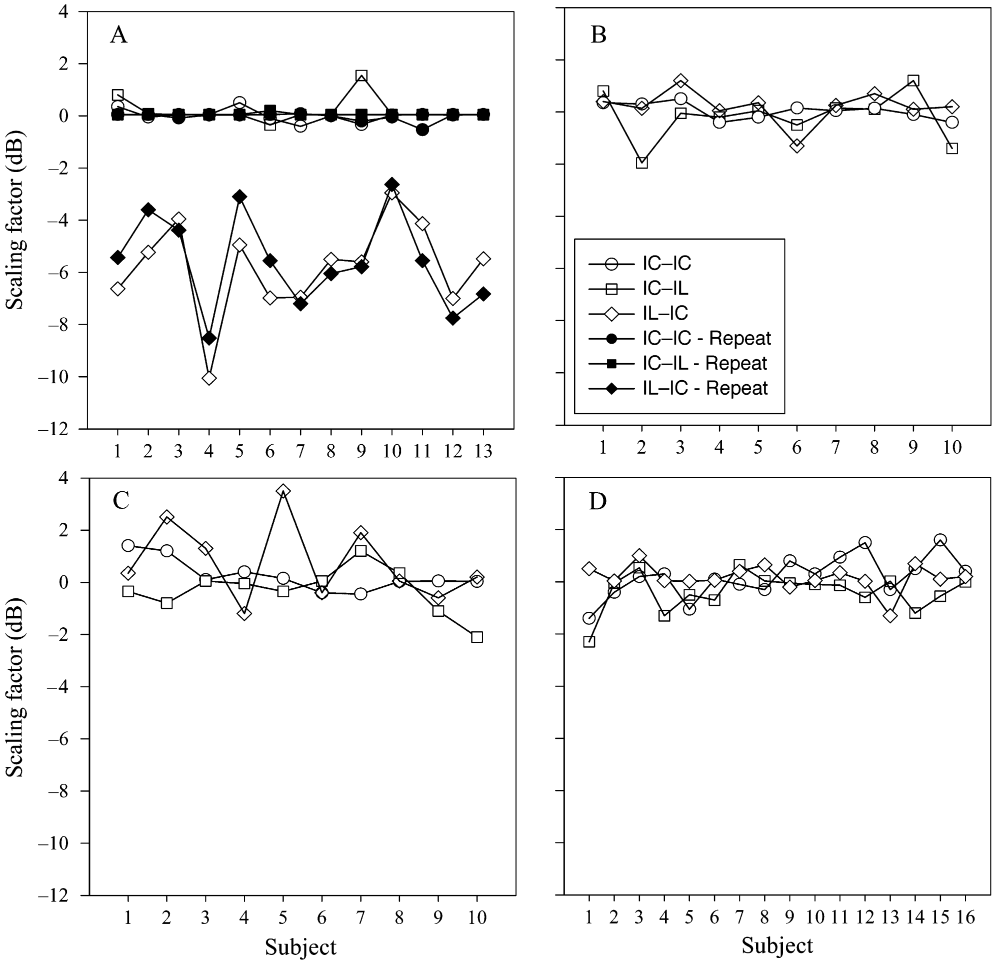

Figure 4. The results from Experiments 2, 3, 4, and 5. The *y*-axis represents the intensity scaling that had to be applied to the second stimulus in order for it to be judged of equal loudness to the first. IC–IC shows the results when the IC stimulus followed the IC stimulus. IC–IL shows the results when the ILLU stimulus followed the IC stimulus. IL–IC shows the results when the IC stimulus followed the ILLU stimulus. (A) Experiment 2: There is a clear difference in the perceived intensity when the IC stimulus follows ILLU, but not when ILLU follows IC. IC–IC-Repeat, IC–IL-Repeat, and IL–IC-Repeat show the results from the IC–IC, IC–IL, and IL–IC conditions, respectively, when the experiment was repeated on a separate visit. (B) Experiment 3: ILLU and IC stimuli consist of single tones. There is no perceived intensity difference when tones are presented in isolation. (C) Experiment 4: ILLU and IC stimuli do not alternate between the ears. There is no perceived intensity difference when the high and low tones do not alternate between the ears. (D) Experiment 5: There is no perceived intensity difference when the ILLU and IC stimuli used in Experiment 2 are separated by 1,200 msec.

Correlational analyses were also performed to examine the effects of musical experience (both listening and playing) and handedness on the amount of scaling required in order for the two stimuli to be judged as being of equal loudness, but no significant effects were found, possibly because our participants did not have a wide enough range of experience.

We conclude that when the illusion-consistent stimulus follows the illusory stimulus (as it did in Ross et al., 1996), it sounds substantially louder than the illusory stimulus, but when the illusory stimulus follows the illusion-consistent stimulus, they sound equally loud.

This result seems counterintuitive: If anything, one might expect the diotic IC stimulus to sound perceptually quieter when immediately preceded by the dichotic ILLU stimulus, but the opposite seems to be true here (see Luce, 1993, or Gulick, Gescheider, & Frisina, 1989, for a brief review of binaural loudness). In Experiment 3, we investigated whether this seemingly reversed intensity difference between the diotic and dichotic stimuli would also hold true for individual rather than sequenced tones. In Experiment 4, we investigated whether this result would hold for a sequence that does not alternate between the ears.

EXPERIMENT 3

Method

Participants. Ten right-handed young adults (3 male, 7 female) from 19 to 30 years of age ($M = 24.3$) participated. All completed questionnaires concerning musical experience and handedness as per the previous experiments. None reported any known hearing loss.

Apparatus and Stimuli. Two monaural pure tones from Experiment 1 (at frequencies of 400 and 800 Hz) were used. The first dichotic complex tone from Experiment 1 (consisting of a 400-Hz tone presented to the left ear and an 800-Hz tone presented simultaneously to the right ear) was also used.

The sound generation equipment, sound-attenuating chamber, and intensity scaling procedure were identical to those used in Experiment 2.

Procedure. The procedure was similar to that from the testing phase of Experiment 2. However, in place of the ILLU stimulus, the single complex (dichotic) tone was presented, and instead of the IC stimulus, one of the two single monaural (diotic) tones was presented. Each participant was presented with only one of the monaural tones throughout the experiment: Five participants had the 800-Hz monaural tone presented to the right ear; 5 participants had the 400-Hz monaural tone presented to the left ear. The participants were presented with three interleaved conditions (diotic–diotic, diotic–dichotic, and dichotic–diotic), as in the previous experiment.

Results and Discussion

Data from Experiment 3 were analyzed in the same way as were the data from Experiment 2, using single-sample t tests. There were no significant differences from 0, or between the diotic–diotic, diotic–dichotic, and dichotic–diotic conditions in the amount of intensity scaling applied to the second stimulus in order for the first and second stimuli to be judged equally loud (diotic–diotic, mean score = 0.039 dB, $n = 10$, $SD = 0.29$; diotic–dichotic, mean score = -0.18 dB, $n = 10$, $SD = 0.89$; dichotic–diotic, mean score = 0.21 dB, $n = 10$, $SD = 0.60$; see Figure 4B).

Correlational analyses were also performed to examine the effects of musical experience (both listening and playing) and handedness on the amount of scaling required for the two stimuli to be judged of equal loudness, but no significant effects were revealed.

Thus, no significant intensity differences were found for any of the three conditions. This result is in contrast to our findings from Experiment 2, indicating that the perceptual asymmetry reported by our participants when the IC stimulus followed the ILLU stimulus is not present when the individual, rather than sequenced, tones are compared. In Experiment 4, we investigated whether this would also be the case when the individual tones are arranged into sequences that do not alternate between the ears.

EXPERIMENT 4

Method

Participants. Ten female adults from 20 to 32 years of age ($M = 25.1$) participated. All were right-handed, and all completed questionnaires concerning musical experience and handedness, as per the previous experiments. None reported any known hearing loss.

Apparatus and Stimuli. The two monaural pure tones from Experiment 3 (at frequencies of 400 and 800 Hz) were used. The complex tone, consisting of a 400-Hz tone presented to the left ear and an 800-Hz tone presented simultaneously to the right ear, was also used. The tones were arranged into sequences to create three stimuli, each comprising 20 tones and lasting 5 sec. The first (dichotic) stimulus mimicked the ILLU stimulus, except that the tones did not alternate between the ears: The 800-Hz tone was always presented to the right ear, and the 400-Hz tone was always presented to the left ear. The second (diotic) stimulus consisted of the 800-Hz tone presented solely to the right ear 20 times. The third (diotic) stimulus consisted of the 400-Hz tone presented solely to the left ear 20 times.

The sound generation equipment, sound-attenuating chamber, and intensity scaling procedure were identical to those used in Experiments 2 and 3.

Procedure. A procedure similar to that for the testing phase from Experiment 2 was used. However, instead of the ILLU stimulus, the dichotic stimulus described above was used, and instead of the IC stimulus, one of the diotic stimuli was presented. To control for side bias, 5 participants had the 800-Hz monaural tone stimulus presented to the right ear, and 5 participants had the 400-Hz monaural tone stimulus presented to the left ear. The participants were presented with three interleaved conditions (diotic–diotic, diotic–dichotic, and dichotic–diotic), as in the previous experiments.

Results and Discussion

There were no significant differences in the data for the 800-Hz and 400-Hz monaural tones, so these data were collapsed. The collapsed data were then analyzed in the same way as the data from Experiments 2 and 3, using single-sample t tests. There were no significant differences from 0 or between the diotic–diotic, diotic–dichotic, and dichotic–diotic conditions in the amount of intensity scaling applied to the second stimulus in order for the first and second stimuli to be judged equally loud (diotic–diotic, mean score = 0.25 dB, $n = 10$, $SD = 0.58$; diotic–dichotic, mean score = -0.31 dB, $n = 10$, $SD =$

0.84; dichotic–diotic, mean score = 0.76 dB, *n* = 10, *SD* = 1.42; see Figure 4C) .

Correlational analyses were also performed to examine the effects of musical experience (both listening and playing) and handedness on the amount of scaling required in order for the two stimuli to be judged of equal loudness, but no significant effects were revealed.

The findings from Experiments 3 and 4 are in contrast to our findings from Experiment 2, in which the diotic IC stimulus had to be attenuated by 7.66 dB in order to be judged of equal loudness to the dichotic ILLU stimulus when the latter was presented first. Rather, there is a nonsignificant trend in the data for the diotic stimuli to be perceived as quieter than the dichotic stimuli, as might be predicted from the literature (e.g., Algom, Adam, & Cohen-Raz, 1988; Algom & Marks, 1984; Reynolds & Stevens, 1960). Thus, the perceived intensity change observed in Experiment 2 is special to the ILLU stimulus, since it was not seen when single, isolated tones were presented instead of a sequence (Experiment 3) or when the high and low tones did not alternate between ears (Experiment 4).

One possible explanation for our data involves nonlinear amplification mechanisms in the peripheral auditory system. We know that the peripheral auditory system is a dynamical system whose gain and degree of nonlinearity can be adjusted under top-down control (e.g., He & Dallos, 2000; Parker & Schneider, 1994; Pickles, 1988). The ILLU stimulus is very unnatural and difficult to encode. It is possible that the auditory system increases its gain in order to try to extract more accurate information from the ILLU stimulus and that it takes a short while to reset this increase in gain back to "normal" levels. We suggest that our participants might have been making intensity judgments on the basis of the final level of the ILLU stimulus when the gain was still increasing and on the basis of the initial level of the IC stimulus before the gain was reset. This may explain why the IC stimulus was perceived as louder when preceded by the ILLU stimulus but not when followed by it if the time required to fully reset the gain was less than the intertrial interval (which was under participants' control but was never allowed to be less than 1,000 msec). However, it is unlikely that such a mechanism would operate over such a long time course this early in the auditory pathway.

Another more likely explanation is that attentional factors were influencing participants' judgments about the intensity of the stimuli with which they were presented. There is evidence in the visual domain that fluency of processing can have an effect on the perceived intensity of a stimulus. Several researchers (e.g., Jacoby & Dallas, 1981; Johnston, Hawley, Plewe, Elliott, & DeWitt, 1990) have reported that more easily perceived items "jump out" from a visual display, appearing to be more intense than they actually are. A subsequent study in the auditory modality by Jacoby, Allan, Collins, and Larwill (1988) indicated that participants often misattribute differences in ease of processing to the level of masking noise, suggesting that ease of processing can also affect the perceived intensity of an auditory stimulus. The ILLU stimulus is very unnatural, and as such it is likely harder to process than the IC stimulus. Hence, when the IC stimulus immediately follows the ILLU stimulus, the IC stimulus, being more fluently processed, might jump out in a similar way, thus sounding much louder than it really is. The time between trials in Experiment 2 might have been long enough to nullify these effects when the IC stimulus preceded the ILLU stimulus. In Experiment 5, we tested the hypotheses above by using a longer interval between the two stimuli that were being compared.

EXPERIMENT 5

Method

Participants. Thirty psychology students (5 male, 25 female) from 19 to 31 years of age (*M* = 23.1) participated in this experiment. All were right-handed. All the participants completed questionnaires concerning musical experience and handedness, as per the previous experiments. None reported any known hearing loss.

Apparatus and Stimuli. The stimuli from Experiment 2 were used. The experiment was run on a Dell 8250 computer using custom in-house software. Participant responses were made via a button-box interface, and responses were recorded on line for later evaluation. The stimuli were presented using Sennheiser HDA 200 audiological headphones that were connected to the computer by a Soundblaster Audigy 2 sound card. Intensity scaling of the stimuli was done on line according to an adaptation of the PEST procedure (Pollack, 1968; Taylor & Creelman, 1967). Intensities ranged from 40 to 75 dB(A), and stimuli were presented over a background noise floor of less than 26 dB(A).

Procedure. The experiment consisted of two phases: screening and testing. Screening followed the same procedure used in Experiment 2. The testing phase also used a procedure similar to that used in Experiment 2, except that the period of silence between the first and second stimuli was 1,200 msec, as compared with 500 msec in Experiment 2. This interval was chosen because it approximated the mean intertrial interval from Experiment 2.

Results and Discussion

Of the 30 participants who signed up for this experiment, 14 failed to pass the initial screening and were excluded from the rest of the study. This number was consistent with the results from Experiments 1 and 2. The remaining 16 participants all completed the testing phase of the experiment. Four of these participants had previously completed Experiment 2.

Data from Experiment 5 were analyzed in the same way as were data from the previous experiments. With the longer interstimulus interval used in Experiment 5, none of the three experimental conditions revealed significant differences in perceived loudness between the two stimuli presented when tested using a single-sample *t* test (IC–IC = 0.193 dB, *n* = 16, *SD* = 0.782; IC–IL = −0.39 dB, *n* = 16, *SD* = 0.713; IL–IC = 0.16 dB, *n* = 16, *SD* = 0.488; see Figure 4D). There were no significant differences between data from the 4 participants who previously participated in Experiment 2 and data from the 12 new participants. These results show that the asymmetry found in Experiment 2 (see Figure 4A) may indeed have been caused either by the auditory system "turning up the gain" to extract information from the hard-to-encode ILLU stimulus or as a result of the fluency of processing pop-out effect described above.

CONCLUSION

Experiment 1 showed that listeners were clearly able to distinguish between the illusory stimulus and one matching its most commonly reported percept (Deutsch, 1974), indicating that listeners were not processing only one channel of information in determining what or where the auditory object was. Rather, the illusory and illusion-consistent stimuli differed in pitch, timbre, location, intensity, or some combination of these attributes, suggesting that a simple suppression model based on one originally proposed by Jeffress (1948, 1972) and extended by Deutsch and colleagues (e.g., Deutsch, 1980, 1981; Deutsch & Roll, 1976) cannot fully account for the octave illusion. Our data suggest that an alternative fusion model proposed by Chambers et al., 2002, 2004) is similarly insufficient. Our findings also provide an alternative explanation for the results reported by Ross et al. (1996), who used MMN to conclude that the octave illusion was created above the level of the auditory cortex. Any distinguishable change in a repeating auditory stimulus would be expected to elicit MMN (Picton et al., 2000), and since our participants were easily able to distinguish between the illusory and illusion-consistent stimuli, the presence of MMN does not allow us to draw any firm conclusions about where in the auditory system the illusion is created.

A variety of percepts elicited by the illusory stimulus have been documented (e.g., Brennan & Stevens, 2002; Chambers et al., 2002, 2004; Deutsch, 1974, 1975, 1978, 1980). Our results indicate that for many individual listeners, the octave illusion is not heard in a stable manner. Whereas half of our participants heard the high tones consistently on the right side, over 40% heard the high tones switch sides more than nine times in 32 trials. Furthermore, the latter group had high false alarm rates when asked to judge whether two successive presentations of identical illusory stimuli were the same or different, again suggesting that for many people, the illusory stimulus is perceived differently on successive presentations. Researchers have also reported that prior musical experience can affect the perception of the octave illusion, with more experienced listeners perceiving it more veridically (Brennan & Stevens, 2002), in agreement with reports of experiential and practice effects for several other illusions (e.g., Robinson, 1972). Thus, it seems that the percept elicited by the octave illusion is not completely "hardwired," but rather it is to some extent a malleable phenomenon, dependent on experience.

In Experiments 2–5, we investigated a new aspect of the auditory illusion not previously reported in the literature. Experiment 2 showed that when listeners were presented with the illusory stimulus, immediately followed by the illusion-consistent stimulus, the illusion-consistent stimulus was perceived as being more than 7 dB louder than the illusory stimulus. This result was obtained despite the fact that the illusory stimulus involved simultaneous stimulation of both ears, whereas the illusion-consistent stimulus involved stimulation of just one ear at a time, and it is in contrast to predictions from studies comparing the loudness of tones presented to one ear versus both ears simultaneously (e.g., Reynolds & Stevens, 1960). Experiments 3–5 showed that this difference in perceived loudness between the illusory and illusion-consistent stimuli disappeared when the tones used in Experiment 2 were presented in isolation rather than in a repeating sequence, when they were presented in sequences that did not alternate between the ears, and when the time interval between the illusory and illusion-consistent stimuli was increased.

The intensity component of the octave illusion likely involves automatic gain-control processes, although the present results cannot distinguish at which level of the auditory system it might operate. Several researchers have described a nonlinear gain-control mechanism whereby the gain structure of the peripheral auditory system can be altered under top-down control. Jacoby and colleagues have described a similar phenomenon operating at a higher level of processing, with easy-to-encode visual stimuli appearing brighter (Jacoby & Dallas, 1981) and easier-to-encode auditory stimuli sounding louder (Jacoby et al., 1988), when compared with more difficult-to-encode stimuli presented at the same intensities. Our studies establish that the gain-control mechanism involved in the intensity part of the octave illusion operates only for sequences of tones less than 1,200 msec apart, since increasing the time between presentations of the illusory and illusion-consistent stimuli to 1,200 msec eliminates the effect.

It is possible, and indeed probable, that in addition to the intensity difference, the illusory and octave-illusion-consistent stimuli differ in pitch (e.g., Chambers et al., 2002), timbre, and/or location, and we are currently investigating these aspects of the octave illusion. We conclude that the octave illusion is more complicated than previously thought, in that it involves complex interactions between the ears, is not necessarily heard in a stable manner, and involves intensity as well as pitch and location.

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NOTES

1. This condition would be "illusion consistent" for participants who heard the high tones in the left ear.

2. The data were also analyzed using *d′* as the dependent measure, and the results were very similar.

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