



The glissando illusion and handedness

Diana Deutsch*, Kamil Hamaoui, Trevor Henthorn

Department of Psychology, University of California, San Diego, La Jolla, CA 92093, United States

Received 26 January 2007; received in revised form 22 May 2007; accepted 25 May 2007

Abstract

This article reports the first study of the glissando illusion, which was created and published as a sound demonstration by Deutsch [Deutsch, D. (1995). *Musical illusions and paradoxes*. La Jolla: Philomel Records (compact disc)]. To experience the illusion, each subject was seated in front of two stereophonically separated loudspeakers, with one to his left and the other to his right. A sound pattern was presented that consisted of a synthesized oboe tone of constant pitch, together with a sine wave whose pitch repeatedly glided up and down (the glissando). These two components alternated continuously between the loudspeakers such that when the oboe tone emanated from the loudspeaker on the left, the glissando emanated from the loudspeaker on the right; and vice versa. The oboe tone was perceived correctly as switching between loudspeakers; however, the segments of the glissando appeared to be joined together seamlessly, such that a single, continuous tone was heard, which appeared to be moving slowly around in space in accordance with its pitch motion. Right-handers ($n = 22$) tended strongly to hear the glissando move between left and right, and also between low and high in space, as its pitch moved between low and high. More specifically, it was frequently heard as tracing an elliptical path aligned diagonally between a position low and to the left when its pitch was lowest, and high and to the right when its pitch was highest. Non-right-handers ($n = 42$) perceived the illusion in statistically different ways. The handedness correlates and other implications of the glissando illusion are discussed.

© 2007 Elsevier Ltd. All rights reserved.

Keywords: Glissando; Sound; Illusion; Handedness; Spatialization

1. Introduction

In our natural environment, we are constantly presented with multiple streams of sound that arise in parallel from different regions of space. In interpreting the complex, time-varying spectra that reach our ears, we have two basic tasks to perform: first, we need to combine together those components of the sound spectra that are emanating from the same source, and to separate out those that are emanating from different sources; i.e., we need to reconstruct *what* sounds are being generated. Second, we need to determine the location of each sound; i.e., to reconstruct *where* each sound is coming from.

Much progress has been made in investigating the types of information employed to determine *what* sounds are being produced in such situations. As is frequently acknowledged, the auditory system here makes extensive use of cues that lead to the most probable conclusions about our sound environment.

As one example, when sounds are presented in succession, those that are proximal in frequency are likely to be coming from the same source; correspondingly, we tend to link together perceptually sounds that are proximal in frequency and to separate out those that are further apart (Bregman, 1990; Bregman & Campbell, 1971; Deutsch, 1975; Van Noorden, 1975). As another example, sounds with similar spectral characteristics are likely to be coming from the same source; correspondingly, we tend to link together successive sounds that are of similar spectral composition and to separate out those with different spectral characteristics (Warren, Obusek, Farmer, & Warren, 1969).

In contrast, although much information has been gathered concerning the ways in which we localize sounds that are presented in isolation, much less is known about the ways in which we localize multiple streams of sound that arise from different locations in space. It has, however, been shown that powerful illusions can be obtained under these conditions (Deutsch, 1974, 1975, 1983a, 1983b; Hartmann & Rakert, 1989; Litovsky, Colburn, Yost, & Guzman, 1999; Wallach, Newman, & Rosenzweig, 1949). Those that are most relevant to the present

* Corresponding author. Tel.: +1 858 453 1558; fax: +1 858 453 4763.
E-mail address: ddeutsch@ucsd.edu (D. Deutsch).

paper are the *octave illusion* (Deutsch, 1974, 1983a, 1983b) and the *scale illusion* (Deutsch, 1975, 1983b).

In the octave illusion, two sinusoidal tones that are spaced an octave apart (at 400 and 800 Hz) are repeatedly presented in alternation. The identical pattern is presented via headphones to both ears simultaneously; however, when the right ear receives the high tone the left ear receives the low tone; and vice versa. A number of illusory percepts are obtained, and the type of percept varies in correlation with the handedness of the listener. The majority of listeners obtain the *simple* percept of a single tone that alternates from ear to ear, whose pitch simultaneously alternates between high and low. In other words, these listeners perceive a single high tone in one ear that alternates with a single low tone in the other ear. Other listeners obtain *complex* percepts, such as two low tones that are close in pitch which alternate from ear to ear, together with an intermittent high tone in one ear. The percepts of right- and left-handers differ statistically in two ways: first, right-handers tend more than left-handers to obtain *simple* percepts. Second, among right-handers who obtain *simple* percepts there is a strong tendency to hear the high tone on the right and the low tone on the left; however, this is not true of left-handers.

In the scale illusion (Deutsch, 1975, 1983b), a major scale, also composed of sinusoidal tones, is presented repeatedly in both ascending and descending form. The pattern is presented via headphones, and its component tones alternate from ear to ear such that when a tone from the ascending scale is in the right ear a tone from the descending scale is in the left ear; and vice versa. Again, a number of illusory percepts are obtained, which vary in correlation with the handedness of the listener. The majority of listeners obtain a *simple* percept that consists of all the tones, heard as two separate melodies – a higher one and a lower one – that move in contrary motion. Furthermore, all the higher tones appear to be coming from one earphone and all the lower tones from the other. Other listeners obtain a variety of *complex* percepts, such as a single stream of tones that correspond to the higher tones but not the lower ones, with the tones localized in a variety of idiosyncratic ways. The illusory percepts experienced by right-handers and left-handers again differ statistically in two ways. First, right-handers tend more than left-handers to obtain *simple* percepts. Second, of those who obtain *simple* percepts, right-handers tend strongly to hear the higher tones as on the right and the lower tones as on the left, whereas this is not true of left-handers.

The present paper reports the first study of the *glissando illusion*, which was created and published as a sound demonstration by Deutsch (1995).¹ To experience this illusion, the listener is seated in front of two stereophonically separated loudspeakers, with one to his left and the other to his right. The sound pattern that gives rise to the illusion consists of two components: a synthesized oboe tone of constant pitch, and a sine wave whose pitch glides up and down. The two components are presented simul-

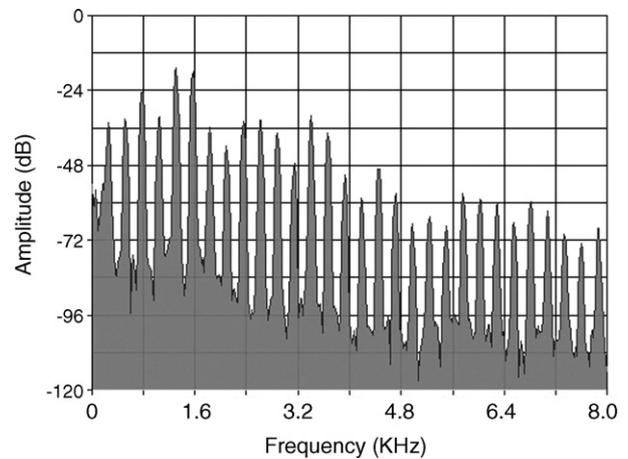


Fig. 1. Sound spectrogram of the synthesized oboe tone.

aneously via the two loudspeakers, and alternate continuously between the speakers such that when the oboe tone is coming from the speaker on the left, a portion of the glissando is coming from the speaker on the right; and vice versa.

As will be shown, the glissando illusion has characteristics that differ from those of the octave and scale illusions in important ways. First, the oboe tone, being rich and broadband in spectrum (Fig. 1) is in principle much better localized than is a sinusoid. It was therefore chosen as one component of the configuration on the hypothesis that it would not be subject to a localization illusion; this hypothesis was confirmed in the present experiment. Second, the octave and scale illusions are both created from steady state tones, which leaves open the question of whether or not a tone of continuously varying frequency would be subject to an illusion with similar characteristics. As will be described, the glissando does indeed give rise to a localization illusion; however, in contrast to the octave and scale illusions it is perceived as moving slowly through space – both between left and right and between high and low – in accordance with its pitch motion.

More specifically, the following hypotheses were addressed in the present experiment: first, informal observations had indicated that the oboe tone was perceived correctly as switching back and forth between the loudspeakers; however, the successive portions of the glissando appeared to be joined together quite seamlessly, so that a single, continuous tone was heard, that appeared to be moving around in space in accordance with its pitch motion. It also appeared from informal observations that there were substantial differences between listeners in terms of the direction of apparent left-right spatial motion of the glissando in relation to its pitch motion. It was hypothesized that despite the phenomenological differences described above, individual differences in perception of the glissando illusion would correlate with handedness, analogous to those for the octave and scale illusions.

Second, it appeared from informal observations that listeners often perceived the glissando as traveling between a high point in space when its pitch was highest and a low point in space when its pitch was lowest. These observations were in accordance with reports by others indicating that sounds of higher pitch were

¹ The booklet accompanying the CD by Deutsch (1995) contained a brief (<200 words) informal description of the glissando illusion, but no formal experimental findings, and no handedness correlates, were reported.

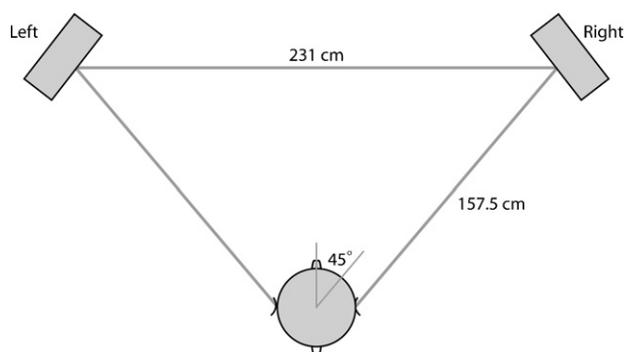


Fig. 2. Seating arrangement for the experiment on the glissando illusion. The subject was seated in front of two loudspeakers, with one to his left and the other to his right.

heard as coming from higher spatial positions and those of lower pitch as coming from lower spatial positions (Pratt, 1930; Roffler & Butler, 1967a; Trimble, 1934). It was therefore hypothesized that the vertical component to the glissando illusion would also be confirmed in a formal experiment.

2. Method

2.1. Subjects

Sixty-four subjects participated in the experiment, and were paid for their services. They were classified as 'righthanded' or 'nonrighthanded' depending on their responses to the handedness questionnaire devised by Varney and Benton (1975). Those who marked at least 9 out of 10 'rights' were classified as 'righthanded', and those who marked 7 or fewer 'rights' were classified as 'nonrighthanded'. In order to produce a clear distinction between the two handedness groups, individuals who marked 8 'rights' on the questionnaire were excluded. Based on this classification, there were 22 right-handers (9 males and 13 females, average age 23.8 years (range 18–36 years), with an average of 2.6 years of musical training (range 0–13 years)) and 42 non-right-handers (19 males and 23 females; average age 21.6 years (range 18–33 years), with an average of 2.2 years of musical training (range 0–10 years)). All subjects had normal hearing, as determined by audiometry. All persons gave their informed consent prior to their inclusion in the study.

2.2. Apparatus

The sound signals were generated on a Kurzweil K2000/V3 synthesizer, and were recorded onto DAT tape using a Panasonic SV-3800 digital audio tape recorder. The tape was played to subjects on a Panasonic SV-3800 digital audio tape recorder, with the signal channeled through a Mackie Designs CR1604 mixer to an NAD-304 stereo integrated amplifier, and then to two Altec-Lansing 3-way loudspeakers. The loudspeakers were elevated on speaker stands 28 cm from the floor, and were separated by a distance of 231 cm. As indicated in Fig. 2, the subject was seated at a location equidistant between the two loudspeakers; the distance between each of the subject's ears and the corresponding loudspeaker was 157.5 cm. Also as indicated, the loudspeakers were placed at an angle of 45° from the center of the subject's head.

2.3. Stimulus parameters

The sound signal comprised two components. The first component consisted of a synthesized oboe tone, with a fundamental frequency at 262 Hz (C₄). A sound spectrogram of the oboe tone is shown in Fig. 1. The second component consisted of a sine wave whose frequency traced a sinusoidal motion covering a two-octave range between 131 Hz (C₃) and 523 Hz (C₅), and with a cycle duration of 2.5 s, as shown in Fig. 3. These two components were alternated between the two loudspeakers at intervals of 238 ms, also as shown in Fig. 3.

The temporal parameters were chosen so that the spatial locations of the different portions of the glissando varied from cycle to cycle. So, for example, the portion of the glissando when its pitch was highest sometimes came from the speaker on the right and sometimes from the speaker on the left. All tones had 5 ms rise times and 15 ms fall times, and the pattern occurred continuously for 2 min without pause. The oboe tone and glissando were identical in amplitude, and were presented at a level of approximately 72 dB SPL at the subject's ears.

2.4. Procedure

All subjects were tested individually. The sound pattern was played for six listening trials; during the first three the subject was facing the loudspeakers—termed *faced-forward*—and during the second three trials the subject was rotated 180°, and so facing away from the loudspeakers—termed *faced-backward*.² (The *faced-backward* condition was included so as to produce an internal control for possible effects of room acoustics or loudspeaker characteristics on the subjects' percepts of left-right asymmetries. The subjects were aware that they were being presented with the identical segment of tape on each listening trial.) Care was taken to ensure that, at the beginning of each trial, the subject's ears were the same distance from the loudspeakers in the two orientations. The subjects were encouraged to remain stationary during the listening trial, but their head movements were not physically constrained.

On each trial, the subject listened to the pattern for at least 20 s, and following that, for as long as he or she wished. The subject then indicated with a nod when he or she was ready to respond. The DAT tape was then paused, and the subject responded. For both the *faced-forward* and the *faced-backward* conditions, on the first listening trial the subject was asked to give a general description of what he or she heard; on the second to describe the oboe tone and how it appeared to be located in space considering all three spatial dimensions (horizontal, vertical and front/back), and on the third to describe the glissando and how it appeared to be located in space, again considering all three spatial dimensions. The subjects accompanied their verbal descriptions with diagrams.

3. Results

3.1. Perception of the oboe tone

As hypothesized, all subjects unequivocally described the oboe tone correctly as alternating between the loudspeakers, in both the *faced-forward* and *faced-backward* conditions.

3.2. Perception of the glissando

All subjects perceived the portions of the glissando as joined together seamlessly, and as moving through space in accordance with its pitch motion. However, there were substantial differences between subjects in the relationship between the pitch motion of the glissando and the direction of its apparent motion through space. These are described below.

² Of the 64 subjects in this study, 3 (2 right-handers and 1 non-right-hander) were tested first in the *faced-backward* position and then in the *faced-forward* position. The statistics were therefore also calculated with these three subjects removed. Again, Fisher's exact probability tests (one-tail) were computed, and essentially the same pattern of results was obtained. The tendency to report *simple* as opposed to *complex* left-right motion was higher among right-handers than among non-right-handers. This tendency was significant in the *faced-forward* position ($p=0.009$) and was present as a non-significant trend in the *faced-backward* position ($p=0.066$). Amongst those who reported *simple* left-right motion, the tendency to hear the higher portion of the glissando as on the right and the lower as on the left was significantly higher among right-handers than non-right-handers, with listeners facing both ways (*faced-forward*: $p=0.0098$; *faced-backward*: $p=0.007$).

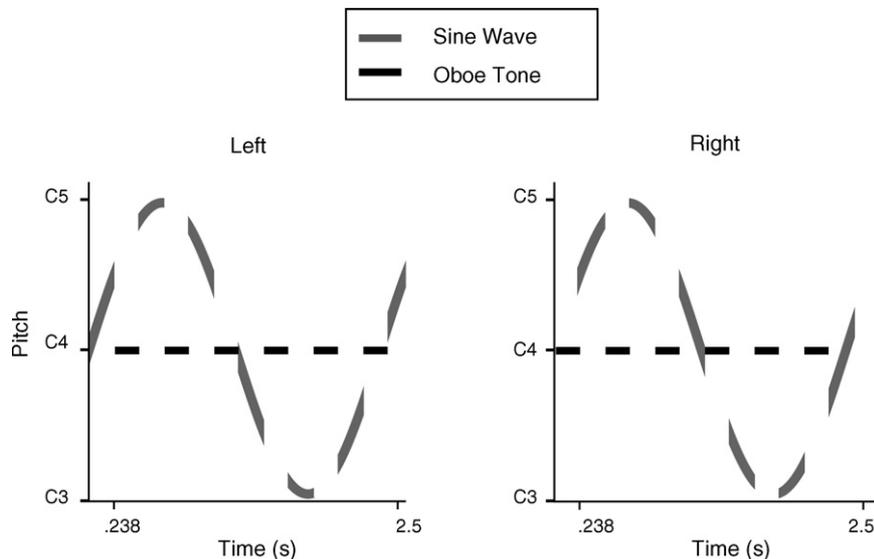


Fig. 3. Fragment of the pattern that gives rise to the glissando illusion, as it was presented in the experiment. The cycle duration of the glissando was 2.5 s, and the segments of the glissando and oboe tone alternated between loudspeakers at intervals of 238 ms.

3.2.1. ‘Simple’ versus ‘complex’ left-right percepts

To classify the different left-right percepts of the glissando, these were first divided into two categories: if the subject heard the glissando as moving in a simple fashion between left and right as its pitch moved between low and high, the percept was designated as *simple*. The remaining percepts were complex and varied; these were designated as *complex*. As an example of a *complex* percept, some subjects heard the glissando as alternating between left and right when its pitch was highest, and as passing in front of them when its pitch was lowest. As another example, some subjects heard the glissando as alternating between left and right when its pitch was lowest, and as passing in front of them when its pitch was highest. *Complex* percepts tended to be unstable, and often changed during the course of a listening trial.

Table 1 shows the percentages of subjects who obtained *simple* left-right percepts, and those who obtained *complex* ones, for the two handedness groups separately. As can be seen, the right-handers tended strongly to obtain *simple* left-right percepts; however, this was not true of the non-right-handers. Since, it had been found for both the octave illusion (Deutsch, 1974) and the scale illusion (Deutsch, 1975) that right-handers tended

Table 1
 Percentages of right-handers and non-right-handers who perceived *simple* left-right motion of the glissando, and percentages of those who perceived *complex* left-right motion

	Types of perceived left-right motion	
	Simple	Complex
Right-handers		
Faced-forward	86%	14%
Faced-backward	73%	27%
Non-right-handers		
Faced-forward	52%	48%
Faced-backward	50%	50%

more than non-right-handers to obtain *simple* left-right percepts, Fisher’s exact probability tests (one-tail) were conducted to evaluate the significance of this handedness difference for the present illusion. The difference between the two handedness groups was found to be significant in the faced-forward position ($p=0.006$) and close to significant in the faced-backward position ($p=0.068$).

To explore a possible effect of musical training, the two handedness groups were subdivided into those who had undergone 3 years or more of musical training, and those who had undergone less than 3 years of training. No difference depending on musical training was found in either handedness group, in either the *faced-forward* or the *faced-backward* condition ($p > 0.05$ for all comparisons).

3.2.2. Patterns of localization for ‘simple’ left-right percepts

We next focus on the *simple* category of left-right percept; that is, the percept of the glissando as moving in a simple fashion between left and right as its pitch moved between high and low. We can enquire whether differences emerged between the two handedness groups in terms of the direction of this apparent motion.

Table 2 shows the percentages of subjects who heard the glissando move between the left side of space when its pitch was lowest, and the right side of space when its pitch was highest (termed ‘Low-left/High-right’), and between the left side of space when its pitch was highest and the right side of space when its pitch was lowest (termed ‘High-left/Low-right’). As can be seen, the right-handers tended strongly to hear the higher portion of the glissando as on the right and the lower portion as on the left; however, the non-right-handers showed no localization preference. Since in both the octave illusion (Deutsch, 1974) and the scale illusion (Deutsch, 1975) the tendency to hear higher tones on the right and lower tones on the left was significantly greater among right-handers than among non-right-handers,

Table 2

Patterns of perceived *simple* left-right motion among right-handers and non-right-handers

	Types of perceived <i>simple</i> left-right motion	
	Low-left/high-right	High-left/low-right
Right-handers		
Faced-forward	84%	16%
Faced-backward	94%	6%
Non-right-handers		
Faced-forward	50%	50%
Faced-backward	52%	48%

'Low-left/High-right' indicates simple motion between left when the pitch of the glissando was lowest, and right when the pitch of the glissando was highest. 'High-left/Low-right' indicates simple motion between left when the pitch of the glissando was highest, and right when the pitch of the glissando was lowest.

Fisher's exact probability tests (one-tail) were conducted to evaluate the significance of this effect for the present illusion. The difference between the two handedness groups was found to be significant in both the faced-forward position ($p = 0.023$) and the faced-backward position ($p = 0.007$).

To explore a possible effect of musical training, the two handedness groups were subdivided into those who had undergone 3 years or more of musical training, and those who had undergone less than 3 years of training. No difference depending on musical training was found in either handedness group ($p > 0.05$ for all comparisons).

3.2.3. Perceptions of elevation

In addition to horizontal motion, the glissando was often perceived as moving along the vertical dimension; specifically, it appeared to be coming from a position high in space when its pitch was high, and from a position low in space when its pitch was low. This percept occurred in 55% of right-handers and 33% of non-right-handers when the subjects were facing the loudspeakers, and in 64% of right-handers and 40% of non-right-handers when the subjects were facing away from the loudspeakers. Although in both cases there was a trend for this effect to occur more frequently among right-handers, the effect was not significant in either case ($p > 0.05$ for both comparisons).

Of those subjects who reported motion along the vertical dimension, 71% obtained *simple* left-right percepts, with the result that they perceived motion simultaneously along both the horizontal and vertical dimensions. As a consequence, many subjects reported that the glissando traced an elliptical path that was aligned diagonally between low and to the left when its pitch was lowest, and high and to the right when its pitch was highest. This illusory percept is illustrated in Fig. 4, which reproduces the diagram drawn by one of the subjects.

3.2.4. Perceptions of front-back motion

Seventeen percent of the subjects also reported hearing the glissando move between a position in front of the subject when its pitch was highest and a position behind the subject when its pitch was lowest. With one exception, all subjects who reported 'front-back' motion obtained *simple* left-right percepts.

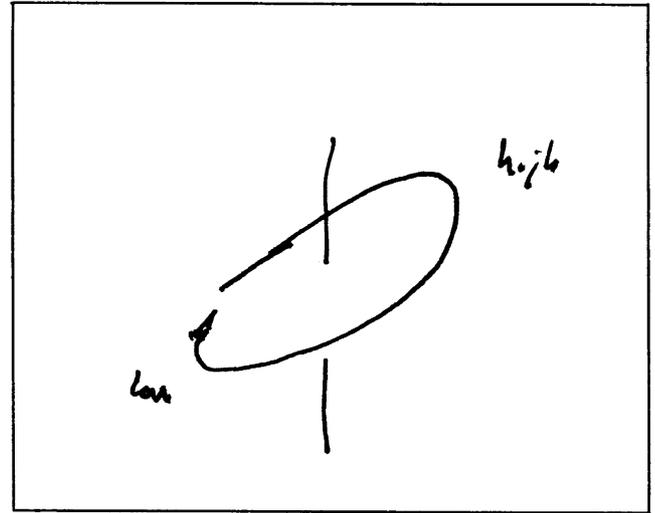


Fig. 4. Diagram drawn by a subject to illustrate his perception of the glissando illusion.

4. Discussion

4.1. General considerations

The glissando illusion, while having certain characteristics in common with the octave and scale illusions, is novel in certain respects. First, whereas on listening to the octave and scale illusions, most listeners perceive patterns of tones that appear to be coming from fixed locations in space, the glissando was here always perceived as moving slowly around in space in accordance with its pitch motion. Further, on listening to the glissando illusion, many subjects obtained a percept that resulted from a synthesis of illusory motion both between left and right and also between high and low. This perceptual synthesis often resulted in subjects perceiving the glissando as tracing an elliptical path aligned diagonally between a position low and to the left, and a position high and to the right, as illustrated in Fig. 4.

Why, then, should the glissando illusion occur? Historically, we can draw on two lines of reasoning. The Gestalt psychologists at the beginning of the last century proposed that we form perceptual configurations based on certain organizational principles, such as proximity and good continuation (see, for example, Wertheimer, 1923). It has more recently been shown that there is a perceptual tendency in various musical contexts to link together sounds that are proximal in pitch, and to separate out those that are further apart (Bregman, 1990; Bregman & Campbell, 1971; Deutsch, 1975; Van Noorden, 1975). There is also some evidence that we tend to link together successive sounds that form continuous pitch trajectories (Divenyi & Hirsh, 1974; Van Noorden, 1975). It can be hypothesized, therefore, that there is a tendency to link together successive portions of the glissando based on these principles, so that we perceive it as a single continuous sound.

A related approach involves the notion of unconscious inference, which was propounded in the nineteenth century by Von Helmholtz (1859), and which has since been applied to many other perceptual phenomena. Basically, it is argued that when

faced with a complex configuration the listener adopts the most plausible interpretation in terms of his knowledge of the environment. In the case of the pattern that produces the glissando illusion, it is extremely unlikely that a sound which changes smoothly in frequency should be switching abruptly between two widely different spatial locations; it is far more likely that such a sound would be coming from a single source that is either stationary or that is moving slowly through space—at least with respect to ourselves. So it can be conjectured that the perceptual system acknowledges the changing spatial position of the glissando, but rejects the hypothesis that it is leaping around widely from one position to another (though this is in fact the case) in favor of the hypothesis that it is moving slowly through space.

It should be noted that two other auditory illusions, the precedence effect (Litovsky et al., 1999; Wallach et al., 1949) and the Franssen effect (Hartmann & Rakert, 1989) can be viewed from a similar perspective. To obtain the precedence effect, the listener is seated facing two loudspeakers, with one to his left and the other to his right. The identical sound pattern is presented via both speakers, but slightly offset in time. When the interval between the two onsets is less than roughly 30 ms (this value differing depending on the stimulus configuration employed) the listener perceives only a single sound pattern, and it appears to be coming from the source of the first-arriving signal. It can be argued that this illusion serves a useful purpose, in that it suppresses unwanted echoes from perception.

To obtain the Franssen effect, the same seating arrangement is employed. A tone of abrupt onset, brief duration, and slow offset is presented from one loudspeaker, while another tone, of gradual onset and long duration, is presented from the other loudspeaker. The listener hears the entire tone complex as a single entity, and as though arising from the loudspeaker that produces the first, brief tone, even though this loudspeaker is silent for most of the time. This illusion is also perceptually useful, since were such a pattern to arrive at our ears in real world situations, it would most likely have emanated from a single source.

Interestingly, the Franssen effect can be surprisingly robust, and persist in face of other cues that could cause the listener to perceive the pattern veridically. An analogous persistence in face of strong contrary evidence occurs in the glissando illusion. The large majority of right-handers tend to perceive the higher portion of the glissando as on their right and the lower portion as on their left, *both* when they are facing the loudspeakers *and* when they are facing the opposite direction. This has the bizarre consequence that the loudspeaker that had appeared to produce the higher component of the glissando now appears to be producing the lower component, and that the loudspeaker that had appeared to produce the lower component now appears to be producing the higher component.

4.2. Hypothesized relationships to cerebral dominance

As described earlier, the handedness correlates found for the glissando illusion can be related to similar handedness correlates for the octave illusion (Deutsch, 1974, 1983a) and scale illusion (Deutsch, 1975). First, for all three illusions, right-handers

tend strongly to obtain *simple* left-right percepts, but this is less true of non-right-handers. Second, for all three illusions, among those who obtain *simple* left-right percepts, there is a strong tendency among right-handers to perceive higher tones as on the right and lower tones as on the left; however, this is less true of non-right-handers. These handedness correlates can be related to findings correlating patterns of cerebral dominance with handedness—findings that have been obtained through studies of patients with brain damage, as well as through the use of the intracarotid amobarbital procedure, functional transcranial Doppler ultrasonography and functional MRI. There is general agreement on two points: first, non-right-handers as a group tend more than right-handers to have bilateral representation of function. Second, whereas strong right-handers tend overwhelmingly to show left hemisphere dominance for speech, this pattern is less consistent among non-right-handers (Hecaen & de Ajuriaguerra, 1964; Isaacs, Barr, Nelson, & Devinsky, 2006; Knecht et al., 2000; Luria, 1969; Milner, Branch, & Rasmussen, 1966; Pujol, Deus, Losilla, & Capdevila, 1999; Rasmussen & Milner, 1977). Given these findings, we can conjecture that there is a tendency to perceive higher tones as on the dominant side of space (i.e., the side of space that is contralateral to the dominant hemisphere) and to perceive low tones as on the non-dominant side.

More specifically, we can note that lesions of both the left and the right hemisphere have resulted in selective mislocalization of sounds in the hemispace contralateral to the lesion (Haeske-Dewick, Canava, & Homberg, 1996; Poirier, Lassonde, Villemure, Geoffrey, & Lepore, 1994; Zatorre, Ptito, & Villemure, 1995). Furthermore, hemispherectomized patients have shown deficits in perception of auditory motion in the hemifield contralateral to the site of hemispherectomy (Poirier et al., 1994, and similar deficits have also occurred following lesions of both the right and the left hemisphere (Bellmann, Clarke, & Assal, 1998; Clarke, Bellmann, Meuli, Assal, & Steck, 2000; Griffiths et al., 1997)). In addition, patients who experience palinacousis tend to perceive the illusory sound as on the side of auditory space that is contralateral to the lesion (Jacobs, Feldman, Diamond, & Bender, 1973), and patients who experience auditory sensations on stimulation of the temporal lobe usually project these sensations to contralateral auditory space (Penfield & Perot, 1963). Furthermore, neuroimaging studies have found that sounds which are perceived laterally in virtual space are associated with activation of the auditory cortex contralateral to the perceived sound (Pavani, Macaluso, Warren, Driver, & Griffiths, 2002). We may therefore conjecture that the present handedness correlates with the glissando illusion reflect greater activity in the dominant hemisphere on the part of neural units that underlie the higher tones, and greater activity in the non-dominant hemisphere on the part of neural units that underlie the lower tones.

4.3. Perceptions of elevation

As described above, many subjects in the present experiment also experienced the glissando as moving upward in space as its pitch ascended, and downward in space as its pitch descended.

This finding is consistent with several earlier reports relating pitch height to impressions of elevation. Pratt (1930) found that a series of tones that ascended in pitch was perceived as moving upwards in space, and Trimble (1934) obtained a similar finding. Roffler and Butler (1967a) replicated this general effect, and reported similar observations from people who were congenitally blind, as well as from young children who were unfamiliar with the use of the terms ‘high’ and ‘low’ with respect to pitch. Considerable interest has since developed in the involvement in sound localization of spectral cues that result from disturbance of incident sound waves by the listener’s head and torso. However, the cues that have been shown to have significant effects have been mostly in higher frequency ranges than those considered here (Butler, 1986; Gardner & Gardner, 1973; Roffler & Butler, 1967b). In addition, experiments on the perceptual significance to sound localization of such cues in the present range have resulted in mixed findings (Algazi, Avendano, & Duda, 2001). It has yet to be determined whether there is any involvement of such spectral cues in perception of the glissando illusion.

4.4. Other reported high-right/low-left associations

In the glissando illusion, as in the octave and scale illusions, right-handers tend to perceive higher tones as to the right and lower tones as to the left. This finding can be related to a study by Mudd (1963), who employed a paradigm in which subjects listened to two tones of different frequency, and then ‘represented’ them by plotting their positions on a two-dimensional spatial array. The subjects assigned higher frequency tones to spatial locations that were higher and to the right, and they assigned lower frequency tones to spatial locations that were lower and to the left. Handedness was not assessed in this study, but it can be assumed that most of the subjects were right-handed.

In another experiment, Rusconi, Kwan, Giordano, Umilta, and Butterworth (2006) found that subjects were faster to respond to higher tones with response keys that were higher and to the right, and faster to respond to lower tones with response keys that were lower and to the left. The vertical effect was statistically significant for both musicians and non-musicians, and the horizontal effect was statistically significant for musicians and showed up as a trend for non-musicians. All the subjects in this study were right-handed.

In considering possible bases for the reaction time advantage found by Rusconi et al. when high tones were associated with keys to the right and low tones with keys to the left, it should be noted that Deutsch (1985) also found a perceptual advantage for ‘high-right/low-left’ configurations over ‘high-left/low-right’ ones when right-handed subjects listened to sequences of dichotic chords and notated the pitches that they heard. Specifically, more pitches were correctly notated when they formed part of a ‘high-right/low-left’ chord than when they formed part of a ‘high-left/low-right’ chord. The reason for the perceptual advantage for ‘high-right/low-left’ configurations can only be conjectured at present, but is consistent with the view that sounds of higher frequency are processed more intensively in the dominant hemisphere, and sounds of lower frequency in the non-dominant hemisphere—a view that would

also explain the illusory displacement of higher sounds to the dominant side of space and lower sounds to the non-dominant side in the glissando illusion.

4.5. Relationship to other studies on separate ‘what’ and ‘where’ pathways

The present findings also relate to the issue of separate *what* and *where* pathways in the auditory system. In the glissando illusion, *what* information is preserved: both the oboe tone and the glissando are perceived correctly. The illusion resides in the *where* component: most of the time, the perceived location of the glissando is quite different from its actual location. This perceptual dissociation can be related to a number of physiological findings. For example, electrophysiological studies on non-human primates have indicated the presence of a ventral *what* pathway, which is distinct from a dorsal *where* pathway (Kaas & Hackett, 2000; Rauschecker & Tian, 2000). In the human case, functional imaging (Alain, Arnott, Hevenor, Graham, & Grady, 2001; Maeder et al., 2001; Warren & Griffiths, 2003; Warren, Zeilinski, Green, Rauschecker, & Griffiths, 2002) and lesion studies (Clarke et al., 2000) have pointed to an anterior *what* pathway, distinct from a posterior *where* pathway.

It should also be noted that in the glissando illusion, *where* a component of the glissando appears to be located is a function of its pitch, so that *what* is here determining *where*. This is consistent with the conjecture that while the *what* and *where* pathways in the auditory system are in a sense distinct and separate, there is nevertheless communication between them (Warren & Griffiths, 2003).

5. Summary and conclusions

In summary, we report a large scale study on a new illusion, which falls into the same class as the octave and scale illusions, but which also differs from these in certain important ways. One component of the stimulus configuration (the oboe tone) is not subject to an illusion, but is heard correctly as alternating between the left and right speakers. The other component (the glissando) is heard as moving slowly through space – most often between low and to the left and high and to the right – in accordance with its pitch motion. (In contrast, on experiencing the octave and scale illusions, the tones are generally perceived as coming from two stable locations in space – one to the left and the other to the right – without a vertical component.) Despite these differences in the nature of the illusion, analogous handedness correlates were obtained. These analogous handedness correlates provide new information concerning the role of cerebral dominance in the localization of complex sound patterns.

More generally, there is much interest in the extent to which individual differences in the perception of music are the result of environmental factors, such as musical training, and the extent to which they are biological in origin (Peretz & Zatorre, 2003). In general, one can reasonably expect that both types of factor operate. However, the finding that individual differences in perception of the glissando illusion correlate with handedness and not with musical training provides evidence that we are

here dealing with a perceptual phenomenon which reflects innate differences in brain organization.

References

- Alain, C., Arnott, S. R., Hevenor, S., Graham, S., & Grady, S. C. L. (2001). 'What' and 'where' in the human auditory system. *Proceedings of the National Academy of Sciences USA*, *98*, 12301–12306.
- Algazi, V. R., Avendano, C., & Duda, R. O. (2001). Elevation localization and head-related transfer function analysis at low frequencies. *Journal of the Acoustical Society of America*, *109*, 1110–1121.
- Bellmann, A., Clarke, S., & Assal, G. (1998). Confrontation between activation and lesion studies in man: The role of anterior insula in auditory motion. *Swiss Archives of Neurology & Psychiatry*, *149*, 80.
- Bregman, A. S. (1990). *Auditory scene analysis: The perceptual organization of sound*. Cambridge: MIT Press.
- Bregman, A. S., & Campbell, J. (1971). Primary auditory stream segregation and perception of order in rapid sequences of tones. *Journal of experimental Psychology*, *89*, 244–249.
- Butler, R. A. (1986). The bandwidth effect on monaural and binaural localization. *Hearing Research*, *21*, 67–73.
- Clarke, S., Bellman, A., Meuli, R. A., Assal, G., & Steck, A. J. (2000). Auditory agnosia and auditory spatial deficits following left hemispheric lesions: Evidence for distinct processing pathways. *Neuropsychologia*, *38*, 797–807.
- Deutsch, D. (1974). An auditory illusion. *Nature*, *251*, 307–309.
- Deutsch, D. (1975). Two-channel listening to musical scales. *Journal of the Acoustical Society of America*, *57*, 1156–1160.
- Deutsch, D. (1983a). The octave illusion in relation to handedness and familial handedness background. *Neuropsychologia*, *21*, 289–293.
- Deutsch, D. (1983b). Auditory illusions, handedness, and the spatial environment. *Journal of the Audio Engineering Society*, *31*, 607–618.
- Deutsch, D. (1985). Dichotic listening to melodic patterns and its relationship to hemispheric specialization of function. *Music Perception*, *3*, 127–154.
- Deutsch, D. (1995). *Musical illusions and paradoxes*. La Jolla: Philomel Records. (compact disc).
- Divenyi, P. L., & Hirsh, I. J. (1974). Identification of temporal order in three—Tone sequences. *Journal of the Acoustical Society of America*, *56*, 144–151.
- Gardner, M. B., & Gardner, R. S. (1973). Problem of localization in the median plane: Effect of pinna cavity occlusion. *Journal of the Acoustical Society of America*, *53*, 400–408.
- Griffiths, T. D., Rees, A., Witton, C., Cross, P. M., Shakir, R. A., Henning, G. B., et al. (1997). Spatial and temporal auditory processing deficits following right hemisphere infarction. A psychophysical study. *Brain*, *120*, 785–794.
- Haeske-Dewick, H., Canava, A. G., & Homberg, V. (1996). Sound localization in egocentric space following hemispheric lesions. *Neuropsychologia*, *34*, 937–942.
- Hartmann, W. M., & Rakert, B. (1989). Localization of sound in rooms IV: The Franssen effect. *Journal of the Acoustical Society of America*, *86*, 1366–1373.
- Hecaen, H., & de Ajuriaguerra, J. (1964). *Left-handedness*. New York: Grune and Stratton.
- Isaacs, K. L., Barr, W. B., Nelson, P. K., & Devinsky, O. (2006). Degree of handedness and cerebral dominance. *Neurology*, *66*, 1855–1858.
- Iverson, P. (1995). Auditory stream segregation by musical timbre: Effects of static and dynamic acoustic attributes. *Journal of Experimental Psychology: Human Perception and Performance*, *21*, 751–763.
- Jacobs, L., Feldman, M., Diamond, S. P., & Bender, M. B. (1973). Palinacousis: Persistent or recurring auditory sensations. *Cortex*, *9*, 275–287.
- Kaas, J. H., & Hackett, T. A. (2000). Subdivisions of auditory cortex and processing streams in primates. *Proceedings of the National Academy of Sciences USA*, *97*, 11793–11799.
- Knecht, S., Drager, B., Deppe, M., Bobe, L., Lohmann, H., Floel, A., et al. (2000). Handedness and hemispheric language dominance in healthy humans. *Brain*, *123*, 2512–2518.
- Litovsky, R. Y., Colburn, H. S., Yost, W. A., & Guzman, S. J. (1999). The precedence effect. *Journal of the Acoustical Society of America*, *106*, 1633–1654.
- Luria, A. B. (1969). *Traumatic aphasia*. The Hague: Mouton.
- Maeder, P. P., Meuli, R. A., Adriani, M., Bellmann, A., Fornari, E., Thiran, J. P., et al. (2001). Distinct pathways involved in sound recognition and localization: A human fMRI study. *NeuroImage*, *14*, 802–816.
- Milner, B., Branch, C., & Rasmussen, T. (1966). Evidence for bilateral speech representation in some nonrighthanders. *Transactions of the American Neurological Association*, *91*, 306–308.
- Mudd, S. A. (1963). Spatial stereotypes of four dimensions of pure tone. *Journal of Experimental Psychology*, *66*, 347–352.
- Pavani, F., Macaluso, E., Warren, J. D., Driver, J., & Griffiths, T. D. (2002). A common cortical substrate activated by horizontal and vertical sound movement in the human brain. *Current Biology*, *12*, 1584–1590.
- Penfield, W., & Perot, P. (1963). The brain's record of auditory and visual experience. *Brain*, *86*, 595–696.
- Peretz, I., & Zatorre, R. (2003). *The cognitive neuroscience of music*. Oxford: Oxford University Press.
- Poirier, P., Lassonde, M., Villemure, J. G., Geoffrey, G., & Lepore, F. (1994). Sound localization in hemispherectomized patients. *Neuropsychologia*, *32*, 541–553.
- Pratt, C. C. (1930). The and spatial character of high and low tones. *Journal of Experimental Psychology*, *13*, 278–285.
- Pujol, J., Deus, J., Losilla, J. M., & Capdevila, A. (1999). Cerebral lateralization of language in normal left-handed people studied by functional MRI. *Neurology*, *52*, 1038–1043.
- Rasmussen, T., & Milner, B. (1977). The role of early left-brain injury in determining lateralization of cerebral speech functions. *Annals of the New York Academy of Sciences*, *299*, 355–369.
- Rauschecker, J. P., & Tian, B. (2000). Mechanisms and streams for processing of 'what' and 'where' in auditory cortex. *Proceedings of the National Academy of Sciences USA*, *97*, 11800–11806.
- Roffler, S. K., & Butler, R. A. (1967a). Localization of tonal stimuli in the vertical plane. *Journal of the Acoustical Society of America*, *43*, 1260–1266.
- Roffler, S. K., & Butler, R. A. (1967b). Factors that influence the localization of sound in the vertical plane. *Journal of the Acoustical Society of America*, *43*, 1255–1259.
- Rusconi, E., Kwan, B., Giordano, B. L., Umiltà, C., & Butterworth, B. (2006). Spatial representation of pitch height: The SMARC effect. *Cognition*, *99*, 113–129.
- Trimble, O. C. (1934). Localization of sound in the anterior posterior and vertical dimensions of auditory space. *British Journal of Psychology*, *24*, 320–334.
- Van Noorden, L. P. A. S. (1975). *Temporal coherence in the perception of tone sequences*. Unpublished doctoral dissertation. The Netherlands: Technische Hogeschool Eindhoven.
- Varney, N. R., & Benton, A. L. (1975). Tactile perception of direction in relation to handedness and familial handedness. *Neuropsychologica*, *13*, 449–454.
- Von Helmholtz, H. (1859/1954). *On the sensations of tone as a physiological basis for the theory of music* (2nd English ed.). New York: Dover.
- Wallach, H., Newman, E. B., & Rosenzweig, M. R. (1949). The precedence effect in sound localization. *American Journal of Psychology*, *62*, 315–336.
- Warren, J. D., & Griffiths, T. D. (2003). Distinct mechanisms for processing spatial sequences and pitch sequences in the human auditory brain. *The Journal of Neuroscience*, *23*, 5799–5804.
- Warren, R. M., Obusek, C. J., Farmer, R. M., & Warren, R. P. (1969). Auditory sequence: Confusions of patterns other than speech or music. *Science*, *164*, 586–587.
- Warren, J. D., Zielinski, B. A., Green, G. G. R., Rauschecker, J. P., & Griffiths, T. D. (2002). Perception of sound-source motion by the human brain. *Neuron*, *43*, 139–148.
- Wertheimer, M. (1923). Untersuchung zur Lehre von der Gestalt II. *Psychologische Forschung*, *4*, 301–350.
- Zatorre, R. J., Ptito, A., & Villemure, J.-G. (1995). Preserved auditory spatial localization following anterior hemispherectomy. *Brain*, *118*, 879–889.