A note about insensitivity to pitch-change direction

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Abstract: Some listeners are insensitive to the direction of pure-tone frequency changes when the standard frequency is roved widely over trials, but less so when the standard frequency is fixed and trial-by-trial feedback is provided. The present experiment tested the hypothesis that fixing the standard frequency and providing feedback is advantageous for direction-impaired listeners because under these conditions the listeners can learn to respond correctly without genuinely perceiving frequency-change direction. This hypothesis was ruled out by the experiment. It appears instead that direction-impaired listeners find it difficult to ignore the irrelevant frequency changes introduced by roving.

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1. Introduction

Identifying the direction of a small frequency change (e.g., of half a semitone) between two sequential pure tones is usually a trivial task for most listeners (e.g., Moore, 1974). However, two studies have reported that some individuals from the normal population—despite having no known audiological or neurological disorder—are unable to identify the direction of such changes, although they have no difficulty in detecting them (Mathias *et al.*, 2010; Semal and Demany, 2006).

Semal and Demany (2006) measured difference limens for frequency (DLFs) in nine listeners. In their main experiment, listeners heard two pairs of pure tones on each trial. In one pair the tones were identical, and in the other the tones differed in frequency. Two tasks were performed in different blocks of trials. In the "detection" task, listeners indicated which pair (first or second) contained the frequency change. In the "identification" task, listeners indicated its direction (up or down). In three listeners, the identification DLF (IDLF) was considerably larger than the detection DLF (DDLF). Thus, these listeners were insensitive to the direction of small frequency changes (or pitch changes, since it was demonstrated that discrimination was almost certainly based on pitch rather than other potential cues). Throughout this article, we refer to listeners displaying this kind of insensitivity as being "direction-impaired."

In Semal and Demany's (2006) experiments, the frequency of the first tone within each pair (the "standard frequency") was always varied randomly ("roved") over a wide range, both between trials and between tone pairs within trials. A more recent study (Mathias *et al.*, 2010) showed that standard-frequency roving was an important feature of the stimuli. The authors found that when roving was removed so that the standard frequency of the pairs was always the same, listeners' impairments in pitch-direction identification were generally much less profound. Moreover, frequency-roving range had a systematic effect on direction-impaired listeners' IDLFs: large impairments in pitch-direction identification tended to occur only when the roving range was widest (400–2400 Hz).

A possible explanation for the role of roving in the foregoing studies is that roving introduced irrelevant pitch changes to the stimulus ensemble (i.e., between the last and first tones of adjacent trials, or between pairs within a trial), and that the direction-impaired listeners were easily confused or distracted by those changes. This "sequential interference" hypothesis is consistent with the fact that, in the study by Mathias *et al.* (2010), the direction-impaired listeners made more errors during identification trials when the between-pair (irrelevant) pitch change and the within-pair (relevant) pitch change had opposite directions than when they had the same direction.

Another explanation is that, when performing the identification task with stimuli that were not roved widely in frequency, direction-impaired listeners were able to make use of the feedback about response accuracy provided after trials. According to this explanation, direction-impaired listeners could not perceive small pitch changes as upward or downward per se in these conditions, but since their DDLFs were smaller than their IDLFs, they could perceive a difference between tone pairs containing small upward and downward changes; owing to the provision of feedback, and to the fact that the stimuli did not vary greatly across trials, the listeners could have learned to label the two different-sounding cases correctly as either "up" or "down," allowing for more successful task performance. Since this strategy requires that the tones forming the up and down cases do not vary greatly across trials, it could explain why IDLFs were elevated considerably relative to DDLFs when the frequency-roving range of the stimuli was wide, but less so when the standard frequency was fixed or the roving range was narrow. The latter explanation, referred to as the "learning" hypothesis, could not be discounted based on the data of Mathias *et al.* (2010) since in their experiments feedback was always provided after trials. Here we report an experiment that provides strong evidence against the learning hypothesis.

2. Methods

2.1 Listeners

Ten listeners (L1–10) took part in the experiment. L1–5 (2 female; age range 25–29 yr) acted as unimpaired controls: all had considerable prior experience in psychoacoustical experiments involving frequency discrimination, and it was known prior to testing that none of them had any difficulty in identifying the direction of small pitch changes. L6–10 (all female; age range 18–53 yr) were direction-impaired listeners. Three of them (L6–8) were listeners L8, L9, and L12 in the study by Mathias *et al.* (2010). The other two listeners (L9 and L10) were listeners L7 and L8 in the study by Semal and Demany (2006). Thus, the direction-impaired group also had considerable experience in frequency-discrimination experiments prior to testing.

All except one listener did not exceed 20 dB hearing level (HL) at frequencies between 250 and 4000 Hz, respectively. L4 had a minor audiometric abnormality, with a threshold of 25 dB HL for 250- and 500-Hz tones in her right ear. Her data are included since all the stimuli in the present experiment were clearly audible to all listeners, and we think that it is very unlikely that the abnormality influenced the results.

2.2 Stimuli and procedure

The experiment was conducted in two different laboratories: L1–3 and L6–8 were tested in York (UK), while L4, L5, L9, and L10 were tested in Bordeaux (France). Except for when differences are stated below, testing procedures in the two laboratories were identical.

In each trial, listeners heard a pair of 250-ms sinusoids, each with a random starting phase and with 20-ms cosine-squared on/off ramps. The level of each tone was randomly set within a 7-dB range around 60 dB sound pressure level. Stimuli were generated digitally and delivered diotically through headphones (UK: Sennheiser HD580; France: Sennheiser HD650) using a 24-bit digital-to-analog converter at a sampling rate of 22 500 Hz (UK) or 44 100 Hz (France). The tones in a trial were separated by an ISI of 250 ms, and differed in frequency by an amount (ΔF) expressed in musical cents (1 cent equals 1/100 of a semitone or 1/1200 of an octave). The direction of the frequency change was equiprobably upward or downward, and listeners were instructed to identify that direction.

The magnitude of ΔF in a run of trials was set initially to 100 cents, and was manipulated within the run using a weighted one-up one-down adaptive procedure that estimated DLFs corresponding to 75% correct on the psychometric function (Kaernbach, 1991). Up to the fifth reversal in the direction of the staircase, ΔF was decreased by a factor of $\sqrt[3]{2.25}$ following a correct response and increased by a factor of 2.25 following an incorrect response. At the fifth reversal onward, down and up step sizes were $\sqrt[3]{1.5}$ and 1.5, respectively. The DLF was defined as the geometric mean of all values visited after the fifth reversal. For the UK listeners, a run ended after the 12th reversal, except if an error was made within the first three trials, in which case two additional first-phase reversals were added to the run; in such cases, the measurement phase started on the seventh rather than the fifth reversal, and ended after the 14th reversal. For the French listeners, the run always ended after the 14th reversal.

Listeners completed 24 runs of trials in the same prescribed order (see Table 1). There were six run phases in the experiment, each containing four runs. Within each of the first five phases (runs 1–20), the frequency of the first tone was fixed at a specific value—either 0, 1551, or 3102 cents above 400 Hz (400, 979.8, or 2400.1 Hz)—that switched at every phase. In the final phase (runs 21–24), the frequency of the first tone on each trial was drawn from a logarithmically flat continuous probability distribution ranging from 400 to 2400.1 Hz. In phase 1 and phases 4–6, responses were followed by visual feedback and a 600-ms pause before the start of the next trial. In phases 2 and 3, visual feedback was omitted and the next trial started 600 ms after the response. Overall, therefore, 24 DLFs per listener were measured. Testing was carried out individually in a sound-attenuating booth, and the listeners completed the experiment in a single session.

3. Results

Figure 1(a) shows the geometric means of each listener's DLFs during each of the six phases of the experiment. The figure indicates that, in L1–5, DLFs were slightly larger when the standard frequency was 400 Hz (phases 2 and 4) than when it was 979.8 or 2400.1 Hz (phases 1, 3, and 5). This finding tallies with the literature on frequency discrimination (e.g., Moore, 1973). L1–5 showed little effect of withholding feedback (phases 2 and 3), and there was only a small increase in their DLFs due to the inclusion of frequency roving (phase 6). This finding is also consistent with previous results (Amitay *et al.*, 2005; Jesteadt and Bilger, 1974; Mathias *et al.*, 2010). L6–10 had generally larger DLFs than L1–5. For these direction-impaired listeners, standard-frequency switching and withholding feedback had little effect on performance, but DLFs increased dramatically after the inclusion of roving. The data were subjected to a

Table 1. Details of the runs of trials in the experiment.

Phase	Runs	Standard frequency (Hz)	Feedback after trials?
1	1–4	979.8	yes
2	5–8	400	no
3	9–12	2400.1	no
4	13–16	400	yes
5	17–20	2400.1	yes
6	21–24	roved	yes

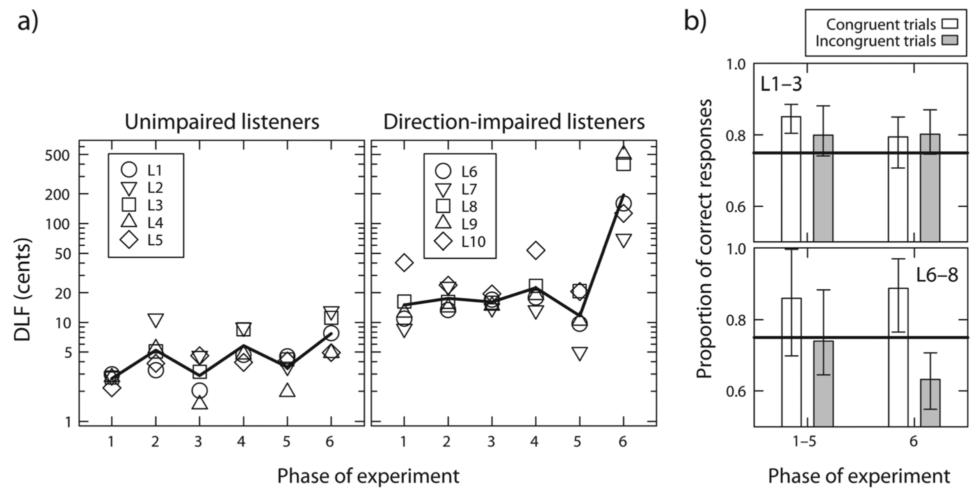

Fig. 1. (a) DLFs from the unimpaired listeners (left panel) and the direction-impaired listeners (right panel). Individual listeners are represented by a specific symbol shape. The abscissa of each symbol represents the run phase, and its ordinate represents the geometric mean of the listener's DLFs over the four runs completed within that phase, on a logarithmic axis. The solid lines represent the group geometric mean DLF per phase. (b) Results of the trial-by-trial analysis. Trials were binned separately for three unimpaired listeners (top panel) and three direction-impaired listeners (bottom panel), separately for phases 1–5 and phase 6, and separately for congruent and incongruent trials. A trial was defined as congruent when the target frequency change had the same direction as the irrelevant frequency change taking place immediately before. Bars represent the group mean proportion of correct responses within the bin, and error bars represent 95% confidence intervals. The horizontal lines represent 75% correct, which was tracked by the adaptive procedure. This analysis was performed using the data from the UK listeners only; for the French listeners, individual trial data were not recorded.

repeated-measures analysis of variance (ANOVA) with run phase (1–6) as a within-subjects factor, group (unimpaired, direction-impaired) as a between-subjects factor, and listeners' log-transformed DLFs per phase as the dependent variable. The ANOVA revealed significant main effects of phase and group, and a significant interaction ($F \geq 9.53$, $p < 0.001$, $\eta^2 \geq 0.54$). Three planned comparisons were used to investigate which levels of the phase factor were driving the phase × group interaction. The planned comparisons were (a) phase 1 versus the mean of phases 2 and 3, (b) the mean of phases 2 and 3 versus the mean of phases 4 and 5, and (c) phase 6 versus the mean of phases 1, 4, and 5. Comparisons (a) and (b) did not reveal significant phase × group interactions ($F \leq 0.75$, $p \geq 0.41$, $\eta^2 \leq 0.09$); this indicates that the effects of standard-frequency switching and withholding feedback on listeners' DLFs were not significantly different between the two groups. By contrast, the interaction was significant for comparison (c) [$F(1, 8) = 19.05$, $p < 0.01$, $\eta^2 = 0.70$]; this indicates that the effect of frequency roving on DLFs was significantly larger in L6–10 than it was in L1–5.

4. Discussion

As shown by Mathias *et al.* (2010) and confirmed in the present experiment, although direction-impaired listeners have great difficulty identifying the direction of small pitch changes in pairs of tones when the standard frequency varies widely from pair to pair, this difficulty is reduced considerably (but not eliminated) when the standard frequency is fixed and trial-by-trial feedback is provided. According to the "learning" hypothesis, this is observed because: (1) when the first element in each pair (i.e., the standard frequency) is always the same, direction-impaired listeners can learn to label upward and downward changes differently without genuinely perceiving them as rising and falling and (2) when the first element differs widely from pair to pair (i.e., the standard frequency is roved), learning is difficult or impossible. This hypothesis implies that direction-impaired listeners should have to re-learn to label the direction of pitch changes whenever the standard frequency is shifted substantially. Moreover, new learning should not occur when these listeners are not provided with the feedback that supposedly allows them to label correctly the different-sounding cases. In the present experiment, switching the standard frequency and withholding feedback did not appear to disrupt the direction-impaired listeners' performance. Note that this could not have come about because the shifts in standard frequency were too small to prevent the generalization of the learned labels to the new stimuli. The standard frequency was shifted by 1551 cents between phases 1 and 2, and between phases 1 and 3. This shift is larger than the mean shift (1034 cents) that took place from trial to trial within phase 6, during which the DLFs measured in L6–10 increased dramatically. Thus, it seems reasonable to rule out the learning hypothesis as an explanation for the effect of roving on the DLFs in direction-impaired listeners.

According to what Mathias *et al.* (2010) called the "sequential interference" hypothesis, L6–10's DLFs were largest in phase 6 because the stimulus ensemble included large irrelevant pitch changes. A trial-by-trial analysis of the data from the UK listeners was performed to test this explanation. For each listener and each run phase, trials completed during the course of the experiment were sorted into two bins depending on whether or not the frequency change between the last tone of the previous trial and the first tone of the current trial was in the same direction as the within-trial (target) frequency change. The bins were collapsed across phases 1–5, since under these conditions the standard frequency was always fixed. The results [Fig. 1(b)] show that during phase 6, the direction-impaired listeners performed very poorly on trials in which the irrelevant change was incongruent with (i.e., opposite to) the direction of the target change. This was not the case during phases 1–5, and was not the case during any phase for the unimpaired listeners. Thus, the present experiment provides further support for the sequential interference hypothesis.

The DLFs measured in L6–10 during phases 1–5 were still markedly larger than those measured in L1–5. One might suppose that, in these first five phases, L6–10 had large DLFs because they simply had difficulty *detecting* the frequency changes, due to factors unrelated to pitch-direction identification. In the previous studies in which these listeners were tested (Mathias *et al.*, 2010; Semal and Demany, 2006), L6–10 did show a slight impairment in the mere detection of frequency changes: their DDLFs were slightly larger than those measured in unimpaired listeners. However, these differences were definitely smaller than the one found during phases 1–5 of the present experiment. Thus, it is likely that L6–10 were to some extent direction-impaired even when the standard frequency was fixed. The pitch-direction impairment could actually explain, at least in part, why L6–10 are also rather poor detectors of frequency changes. As suggested by Semal and Demany, frequency changes may be detected most efficiently by a mechanism incorporating a sensitivity to pitch-change direction; sub-optimal detection of frequency changes may thus be expected in listeners with reduced sensitivity to the direction of pitch changes.

It is worth pointing out that none of the direction-impaired listeners tested in the present experiment seemed to suffer from congenital amusia. Previous studies have suggested that poorer pitch-direction identification than pitch-change detection is a characteristic of this disorder (Foxton *et al.*, 2004; Liu *et al.*, 2010). These studies always used a fixed standard frequency. It would be interesting to determine whether insensitivity to pitch-change direction observed in amusics is also more pronounced when the standard frequency is roved.

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References and links

Amitay, S., Hawkey, D. J. C., and Moore, D. R. (**2005**). “Auditory frequency discrimination learning is affected by stimulus variability,” Percept. Psychophys. **67**, 691–698.

Foxton, J. M. (**2004**). “Characterization of deficits in pitch perception underlying ‘tone deafness,’ ” Brain **127**, 801–810.

Jesteadt, W., and Bilger, R. C. (**1974**). “Intensity and frequency discrimination in one- and two-interval paradigms,” J. Acoust. Soc. Am. **55**, 1266–1276.

Kaernbach, C. (**1991**). “Simple adaptive testing with the weighted up-down method,” Percept. Psychophys. **49**, 227–229.

Liu, F., Patel, A. D., Fourcin, A., and Stewart, L. (**2010**). “Intonation processing in congenital amusia: Discrimination, identification and imitation,” Brain **133**, 1682–1693.

Mathias, S. R., Micheyl, C., and Bailey, P. J. (**2010**). “Stimulus uncertainty and insensitivity to pitch-change direction,” J. Acoust. Soc. Am. **127**, 3026–3037.

Moore, B. C. J. (**1973**). “Frequency difference limens for short-duration tones,” J. Acoust. Soc. Am. **54**, 610–619.

Moore, B. C. J. (**1974**). “Relation between critical bandwidth and frequency-difference limen,” J. Acoust. Soc. Am. **55**, 359–359.

Semal, C., and Demany, L. (**2006**). “Individual differences in the sensitivity to pitch direction,” J. Acoust. Soc. Am. **120**, 3907–3915.