

Studies of pitch mechanisms based on perceptual learning

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Mechanisms of pitch perception were studied using perceptual learning. In one set of studies, subjects discriminated the fundamental frequency (F0) of a target group of harmonics embedded in a background of harmonics with fixed F0. The results were potentially affected by pitch discrimination interference (PDI) and by cues related to pitch pulse asynchrony (PPA) between the target and background. Large learning effects occurred when PPA cues were available. Training was given using a stimulus with cosine-phase harmonics and high harmonics in the target, under conditions where PPA was not useful. Learning occurred, and it transferred to other cosine-phase, but not to random-phase, tones. The learning may reflect improvements in the ability to overcome PDI. In a second set of studies, F0 discrimination was measured for tones with cosine- or random-phase harmonics, bandpass filtered with five harmonics within the passband and presented in threshold-equalizing noise. Groups trained with LOW, MID, or MID-HIGH stimuli (harmonics 1-5, 11-15, or 14-18, respectively) showed learning effects that transferred to other stimuli except HIGH (28-32). A group trained with HIGH stimuli showed no learning effect, suggesting that a different mechanism was used for the HIGH stimuli than for the other stimuli. We propose that the LOW, MID, and MID-HIGH stimuli were discriminated using temporal fine structure information.

INTRODUCTION

This chapter describes a series of experiments in which perceptual learning was used to assess mechanisms of pitch perception for complex tones. It is widely believed that the pitch of complex tones containing low harmonics (below about the 8th), which are resolved in the peripheral auditory system (Plomp, 1964; Moore and Gockel, 2011), is derived from place and/or temporal information (patterns of phase locking) about the frequencies of the individual harmonics (Goldstein, 1973). Evidence for the involvement of phase locking comes from studies showing that the ability to ‘hear out’ individual components from complex sounds worsens at high frequencies, and even widely spaced components are difficult to hear out when their frequencies fall above 5 kHz (Moore *et al.*, 2006). Also, the pitch of a mistuned harmonic in a complex tone can be predicted using a model combining the effects of excitation pattern interaction and neural timing (Hartmann and Doty, 1996).

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For complex tones containing only very high harmonics (above about the 15th), the pitch is assumed to be based on the temporal envelope evoked on the basilar membrane by interfering harmonics (Moore and Moore, 2003a; de Cheveigné, 2005; Plack and Oxenham, 2005; Moore, 2012). There is less agreement about the mechanism that determines the pitch of complex tones with harmonics in the range 8-15. Some authors have argued that the pitch of such tones is derived from the temporal fine structure (TFS) of the waveform evoked on the basilar membrane by the interference of two or more harmonics (Schouten, 1940; Schouten *et al.*, 1962; Moore *et al.*, 2009). This idea is illustrated in Fig. 1. If this is the case, then the pitch mechanism might be similar for complex tones containing low, resolved, harmonics and for complex tones containing harmonics in the range 8-15.

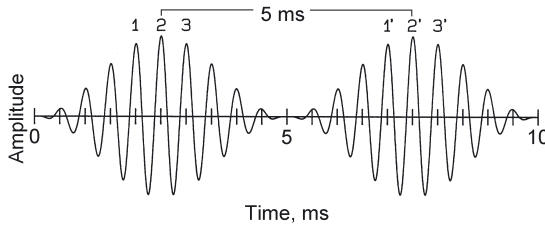


Fig. 1: Simulation of the waveform evoked on the basilar membrane at a place tuned to 2000 Hz by a complex tone with $F_0 = 200$ Hz. Nerve spikes occur close to prominent peaks in the TFS (labelled 1, 2, 3 and 1', 2', and 3'). The pitch is assumed to be determined from the time interval between peaks close to adjacent envelope maxima (5 ms).

We have used perceptual learning to explore whether there are different pitch mechanisms for tones containing low, intermediate, and high harmonics. The rationale is that, if there are different pitch mechanisms, then training on fundamental frequency (F_0) discrimination of tones with, for example, high harmonics will lead to improvements in performance only for tones with high harmonics; the training will not lead to better performance (i.e., transfer) to tones with low or intermediate harmonics because of the different mechanisms involved. However, if there is a single pitch mechanism for low, intermediate, and high harmonics, then training using tones with high harmonics might transfer to tones with low or intermediate harmonics, and vice versa. This rationale has been applied in a series of studies that are summarised below.

F_0 DISCRIMINATION OF A GROUP OF HARMONICS EMBEDDED IN A BACKGROUND OF HARMONICS WITH FIXED F_0

Several researchers have presented evidence suggesting that some harmonics are more important than others in determining the pitch of complex sounds (Plomp,

1967; Ritsma, 1967; Moore *et al.*, 1985). The harmonics that are most important are called the ‘dominant’ harmonics, and the frequency region in which they fall is called the ‘dominant region’. In one series of studies (Miyazono and Moore, 2009; Miyazono *et al.*, 2010), we used stimuli similar to those that have been used to determine the dominant region. Thresholds for detecting a change in F0 (F0DLs) were measured for a group of harmonics (group B) embedded in a group of fixed non-overlapping harmonics (groups A and C) with the same mean F0. A schematic spectrum for one such stimulus is shown in Fig. 2.

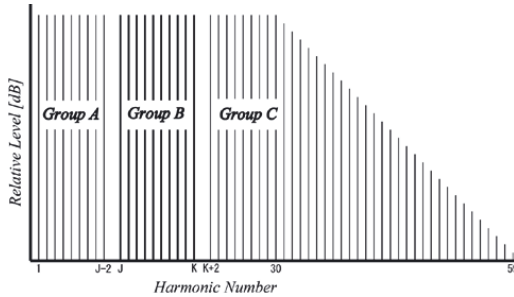


Fig. 2: Schematic spectrum showing components in groups A, B and C.

In the first experiment (Miyazono and Moore, 2009), a low F0 of 50 Hz was used. Group B contained harmonics 1-5, 1-25, 6-30, or 26-30. For the first two of these stimuli, there were no components in group A. The first two of these stimuli contained some resolved harmonics in group B, the third contained intermediate harmonics, and the fourth contained only completely unresolved harmonics. The components of the complex sound were added either starting with random phases or all starting in cosine phase (90°); the latter leads to a waveform with a high peak factor on the basilar membrane when the components are unresolved. In what follows, when ‘group’ forms part of a label referring to a stimulus it is spelled with a lower-case g, whereas when it refers to a group of subjects, it is written with an upper case G. One group of subjects was trained over multiple days using cosine-phase complex tones with harmonics 26-30 in group B (Group UC, unresolved-cosine). A second group was trained using random-phase complex tones with harmonics 1-5 in group B (Group RR, resolved-random). Group UC showed large improvements during training, which did not transfer to the other conditions tested (as assessed in the post-training session). Group RR did not show any clear improvement with training.

At first sight, these results might be taken as supporting the idea that there are different pitch mechanisms for low and high harmonics, as learning occurred only for the complex tones with high unresolved components in group B, and the learning did not transfer to complex tones with low harmonics in group B. However, Miyazono and Moore (2009) suggested an alternative explanation of the results. F0

discrimination of the cosine-phase tones with high harmonics might have been based on a cue called ‘pitch-pulse asynchrony’ (PPA) (Gockel *et al.*, 2005). Subjects may compare the timing of envelope peaks across different auditory filters. Consider, for example, an auditory filter centred on the 20th harmonic, within group A. For the cosine-phase stimuli, this would produce envelope peaks every 20 ms. For an auditory filter centred on the 28th harmonic, within group B, the envelope peaks would initially be synchronized to those of group A. However, in the interval where the F0 was shifted upwards, the period would be shorter, and towards the end of the stimulus the envelope peaks at the output of the filter centred in group B would occur earlier in time than those for the filter centred in group A; in other words, a PPA would occur. In the interval where the F0 was shifted downwards, a PPA in the opposite direction would occur. Thus, there would be a PPA across auditory filters, which would differ for the two intervals of a trial. The use of a cue based on PPA could account for the finding that, after training, thresholds for F0 discrimination of the cosine-phase complex tones with harmonics 26-30 in group B were very low, being below 0.1% of the F0 for several subjects.

Miyazono *et al.* (2010) confirmed that the learning effect found by Miyazono and Moore (2009) was indeed based on the use of a cue related to PPA. When PPA cues were disrupted by introducing a random temporal offset between the envelope peaks of the harmonics in group B and the remaining harmonics, F0DLs increased markedly.

Miyazono *et al.* (2010) examined perceptual learning using a training stimulus with cosine-phase harmonics, F0 = 50 Hz, and high harmonics in group B, under conditions where PPA cues were disrupted, as described above. Learning occurred, and it transferred to other cosine-phase tones, but not to random-phase tones. A similar experiment with F0 = 100 Hz showed a learning effect that transferred to a cosine-phase tone with mainly high unresolved harmonics, but not to cosine-phase tones with low harmonics, and not to random-phase tones. The learning found by Miyazono *et al.* (2010) appeared to be specific to tones for which F0 discrimination was based on distinct peaks in the temporal envelope.

A complication with the experiments described so far is that the results were almost certainly influenced by pitch discrimination interference (PDI), which is the phenomenon that F0 discrimination of a group of harmonics in one frequency region can be impaired by harmonics with a fixed (but nearby) F0 in a different region (Gockel *et al.*, 2004; 2009b). The learning effect found might partly reflect learning to overcome the interference produced by the harmonics in groups A and C. The experiments described next were intended to avoid this complication.

F0 DISCRIMINATION OF BANDPASS-FILTERED COMPLEX TONES IN BACKGROUND NOISE

Miyazono and Moore (2013) examined whether the pitch mechanism for tones with intermediate harmonics is similar to or different from the mechanisms for low and high harmonics. We studied perceptual learning for F0 discrimination using complex

tones that were bandpass filtered so as to contain low resolved harmonics (stimulus LOW), high unresolved harmonics (stimulus HIGH), and intermediate harmonics (stimulus MID). All stimuli were presented in a background of threshold equalizing noise (TEN) (Moore *et al.*, 2000) to mask combination tones and to limit the audibility of components falling outside the passband.

Learning effects with harmonics 11-15 in the MID stimulus

In experiment 1, the filters were chosen to have relatively shallow slopes of 30 dB/oct so that, when the harmonics were unresolved, changes in F0 would result in minimal changes in the excitation pattern (Moore and Moore, 2003a; 2003b). Also, the use of shallow slopes meant that there were no ‘edge’ harmonics (harmonics with no adjacent harmonics above or below them), avoiding the possibility that edge harmonics might be unusually well resolved (Moore and Ohgushi, 1993).

Subjects were required to discriminate the F0 of two successive tones presented at 65 dB SPL. The nominal F0 was 100 Hz. Three fixed spectral envelopes were used, each with a flat bandpass region and slopes of 30 dB/oct. The passbands extended from 100 to 500, 1100 to 1500, and 2800 to 3200 Hz for cases LOW, MID, and HIGH, respectively. All components were added with cosine starting phase. The TEN spectrum ranged from 100 to 8000 Hz. The TEN level at 1 kHz, expressed as dB/ERB_N (Moore, 2012), was set 20 dB below the level of the each component within the passband.

There were three groups of five young normal-hearing subjects, designated LOW, MID and HIGH, according to the stimuli used during training. Each subject was tested on 10 days, two for measurement of pre-training thresholds for all three conditions (LOW, MID, and HIGH), six for training with the stimulus allocated to that group (usually on successive days, but excluding weekends), and two for measurement of post-training thresholds.

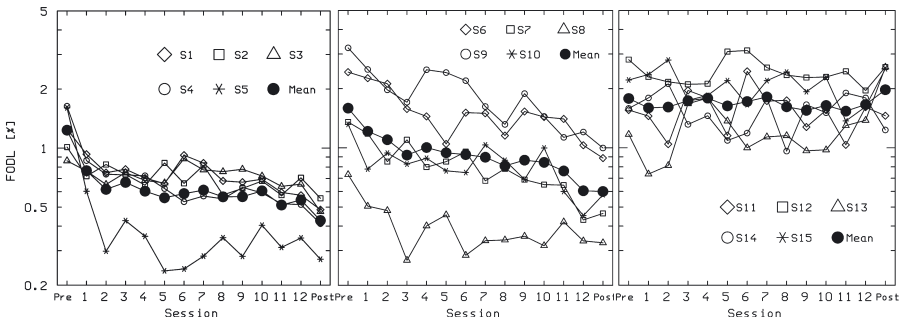


Fig. 3: Results obtained for the pre-training session (Pre), the training sessions, and the post-training session (Post), for Groups LOW (left), MID (middle) and HIGH (right). The F0DLs for the Pre and Post sessions are for the same stimuli as used during training.

Fig. 3 shows the results obtained for the pre-training session (Pre), the training sessions, and the post-training session (Post), for each group. Thin curves show geometric mean F0DLs for the individual subjects (based on at least three estimates for pre- and post-training sessions, and six for training sessions), and curves marked by large filled circles show the geometric mean across subjects. The F0DLs are expressed as relative values in % ($100 \times \Delta F/F_0$). Performance improved across days for Groups LOW and MID, but not for Group HIGH.

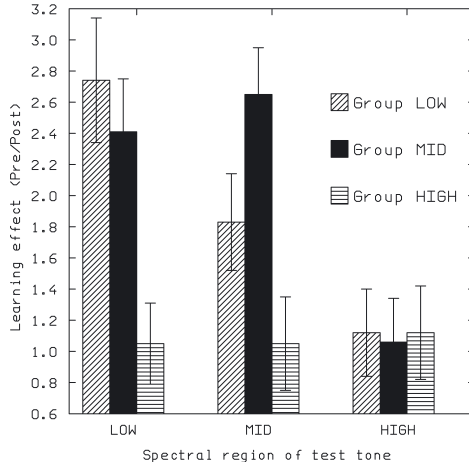


Fig. 4: Learning and transfer effects for each group. Each set of three bars denotes one stimulus type. Error bars indicate ± 1 standard error (SE).

Fig. 4 shows the overall learning effect for each group and each stimulus type, expressed as the mean F0DL for the pre-training session divided by the mean F0DL for the post-training session. The three sets of bars represent the three stimulus cases, and the three bars within each set represent the three groups. Group LOW showed a large learning effect for the LOW stimuli, with strong transfer to the MID stimuli, but no transfer to the HIGH stimuli. Group MID showed a large learning effect for the MID stimuli, with strong transfer to the LOW stimuli and no transfer to the HIGH stimuli. Group HIGH showed no learning effect for any stimuli. The fact that there was no learning effect for Group HIGH, while there was for Groups LOW and MID, suggests that the mechanism underlying F0 discrimination was different for the HIGH stimuli than for the LOW or MID stimuli.

The passband for stimulus MID contained harmonics 11 to 15. The harmonics in this stimulus were largely unresolved, and F0 discrimination was probably based on TFS information derived from unresolved harmonics. Hence, the similarity of the learning effect for cases LOW and MID, and the transfer of learning between these two cases, supports the idea that F0 discrimination was based on a common

mechanism, probably using TFS information (from resolved harmonics for stimulus LOW and unresolved harmonics for stimulus MID). However, harmonics 7, 8, 9, and 10, which fell on the slope below the passband, would have been above the masked threshold in the TEN. Bernstein and Oxenham (2003) suggested that harmonics up to the 10th might be resolved. It is possible, therefore, that the lowest audible harmonics in stimulus MID were resolved to some extent. This could account for the similarity of the results for the LOW and MID stimuli, and the transfer of learning for these two types of stimuli. To assess this possibility, Miyazono and Moore (2013) measured learning and transfer effects using a new MID stimulus, which is described below.

Learning effects with harmonics 14-18 in the MID stimulus

In experiment 2, the new MID stimuli, denoted MID-HIGH, were filtered so that the passband contained harmonics 14-18. In addition, the spectral slope on the low side of the passband was made steeper, being 60 dB/oct rather than 30 dB/oct. This meant that fewer harmonics falling on the lower slope were above the masked threshold in the TEN. The lowest audible harmonic in the MID-HIGH stimuli was the 11th. This would not have been resolved, but the frequency region of the lowest audible harmonics might have been low enough for TFS information to be used. Seven new subjects were tested, denoted Group MID-HIGH. Training was performed only for the MID-HIGH stimuli, and transfer of learning to the LOW and HIGH stimuli was assessed. Only cosine-phase stimuli were used.

The left panel of Fig. 5 shows the learning curves. The group mean results improved significantly across days. Most individual subjects also showed improvements, but with marked variability. The right panel of Fig. 5 shows the learning and transfer effects. There was a large learning effect for the MID-HIGH stimuli, with strong transfer to the LOW stimuli and no transfer to the HIGH stimuli.

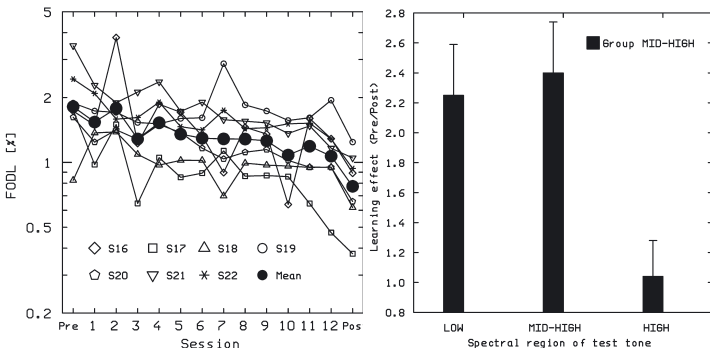


Fig. 5: The left panel shows F0DLs for the pre-training session (Pre), the training sessions, and the post-training session (Post), for each subject (open symbols) and for the mean (filled circles). The right panel shows learning and transfer effects for each stimulus type. Error bars indicate ± 1 SE.

The pattern of the results is the same as for experiment 1, despite the fact that all harmonics for stimulus MID-HIGH would have been unresolved. This supports the interpretation that the transfer of learning between stimuli MID and LOW and between MID-HIGH and LOW reflects a common underlying mechanism based on the use of TFS information.

Learning effects for random-phase tones

Experiments 1 and 2 were conducted using stimuli whose components were added in cosine starting phase, which leads to a waveform on the basilar membrane with a high peak factor when the components are not resolved. Experiment 3 was conducted to assess the importance of the peak factor. Components were added with random starting phase. This leads to a waveform on the basilar membrane with a lower peak factor than for cosine phase when the components are not resolved. Effects of component phase on F0 discrimination should only occur when the components on which discrimination is based are at least partly unresolved, so the results were intended to provide an additional check that the components for stimulus MID-HIGH were unresolved. The passbands extended from 100 to 500, 1400 to 1800, and 2800 to 3200 Hz, for cases LOW, MID-HIGH, and HIGH, respectively. Three groups of four (new) subjects were tested, designated LOW, MID-HIGH, and HIGH, according to the stimuli used during training.

The left panel of Fig. 6 shows the mean learning curves for each group. There was a clear improvement across sessions for Groups LOW and MID-HIGH, but not for Group HIGH. The mean F0DLs for Group HIGH were significantly higher than were obtained for Group HIGH in experiment 1, indicating that F0DLs based on temporal-envelope cues are affected by the peak factor of the waveform on the basilar membrane, which is consistent with previous work (Houtsma and Smurzynski, 1990; Wang *et al.*, 2012). Also, the mean F0DLs for Group MID-HIGH were significantly higher than the F0DLs for Group MID-HIGH in experiment 2, confirming that the components in stimulus MID-HIGH were at least partially unresolved.

The right panel of Fig. 6 shows the learning and transfer effects. Group LOW showed a large learning effect for the LOW stimuli, with some transfer to MID-HIGH and no transfer to the HIGH stimuli. Group MID-HIGH showed a large learning effect for the MID-HIGH stimuli, with some transfer to LOW and no transfer to the HIGH stimuli. Group HIGH showed no learning effect and no transfer to either of the other stimuli. The pattern of the learning and transfer effects was similar to that for experiments 1 and 2, indicating that the peak factor of the stimuli is not critical in determining whether or not learning and transfer of learning occur.

DISCUSSION

In the experiments with bandpass-filtered tones, F0DLs for tones with low harmonics improved with training, consistent with the results of Grimault *et al.* (2002). However, Grimault *et al.* also found a learning effect for tones with only

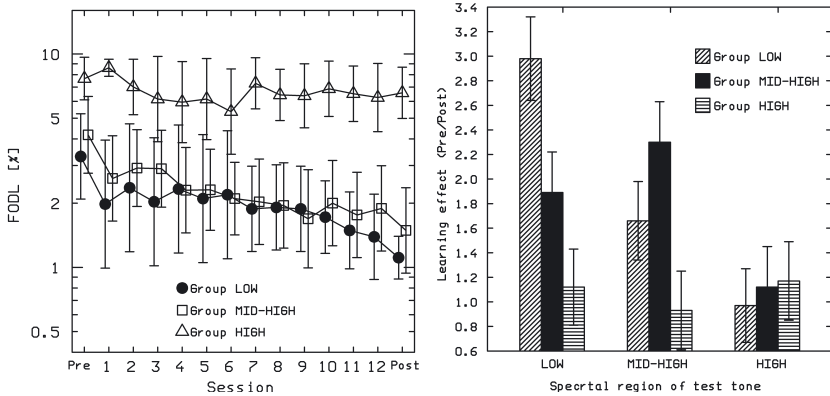


Fig. 6: The left panel shows mean results obtained for the pre-training session (Pre), the training sessions, and the post-training session (Post), for each group. The F0DLs for the Pre and Post sessions are for the same stimuli as used during training. The right panel shows learning and transfer effects for each group and stimulus type. Error bars indicate ± 1 SE.

high harmonics, while experiments 1 and 3 showed no such effect. The difference may have occurred because our subjects were tested using more trials during the pre-training sessions, which would have allowed fast perceptual learning (Hawkey *et al.*, 2004) and procedural learning. The learning effects found by Grimault *et al.* might have reflected fast perceptual and procedural learning. The results of experiments 1 and 3 also differ from those obtained for F0 discrimination of a group of harmonics embedded within harmonics whose F0 was fixed (Miyazono *et al.*, 2010), as described earlier in this chapter. For the earlier results, a learning effect was found when group B contained only high harmonics, but such an effect was not found in experiments 1 and 3. The difference probably reflects differences in the stimuli: discrimination of the F0 of a group of harmonics embedded within harmonics whose F0 was fixed in the earlier study, versus discrimination of a group of harmonics presented in TEN in the later study. In the earlier study, the learning may have involved reduction of PDI (Gockel *et al.*, 2004; 2009a). PDI seems to depend on the relative salience of the target and interfering sounds, and so PDI would have been strong when group B contained only high unresolved harmonics. It may be that effects of training on PDI are large when the PDI effect itself is large. When group B contained harmonics 1-5, the harmonics in group B would have had a higher pitch salience than those in groups A and C (Jackson and Moore, 2013), leading to a small PDI effect, and therefore to little scope for reducing PDI by training.

The experiments using bandpass-filtered tones included stimuli (MID and MID-HIGH) with intermediate harmonic numbers. In experiment 1, the lowest harmonic within the passband was the 11th, and the lowest component that was above

threshold in the TEN was the 7th. In experiment 2, the lowest harmonic within the passband was the 14th, and the lowest harmonic that was above threshold in the TEN was the 11th. It seems likely that only harmonics up to the 8th are resolvable (Plomp, 1964; Plomp and Mimpen, 1968; Moore and Ohgushi, 1993; Moore *et al.*, 2006; Moore and Gockel, 2011), and the limit may be even lower for complex tones with low F0 (Jackson and Moore, 2013). Even if harmonics up to the 10th are resolvable (Bernstein and Oxenham, 2003), the audible harmonics in the MID-HIGH stimulus were almost certainly only unresolved. Consistent with this, F0 discrimination of the MID-HIGH stimuli was better when the components were added in cosine phase (experiment 2) than when they were added in random phase (experiment 3). The results showed clear learning effects for the LOW, MID, and MID-HIGH stimuli, and these effects transferred; training with LOW stimuli led to better F0 discrimination of MID stimuli, and training with MID or MID-HIGH stimuli led to better discrimination of LOW stimuli. This is consistent with the idea that F0 discrimination of the LOW, MID, and MID-HIGH stimuli was based on similar mechanisms, perhaps based on the use of TFS information. For the LOW stimuli, the TFS would have conveyed information about the frequencies of individual harmonics, whereas for the MID and MID-HIGH stimuli, the TFS would have conveyed information about the time intervals between prominent peaks in the waveform produced by the interaction of harmonics on the basilar membrane (Schouten *et al.*, 1962), as illustrated in Fig. 1. However, the two types of TFS information may be used in a similar way by the pitch processor (Meddis and O'Mard, 1997; Bernstein and Oxenham, 2005; Moore, 2012).

The results showed no learning effects for the HIGH stimuli, suggesting that the mechanism underlying discrimination of such stimuli is different from that for the LOW, MID, and MID-HIGH stimuli. It seems likely that F0 discrimination of the HIGH stimuli was based on envelope information only, not TFS information or information from resolved harmonics (Moore and Moore, 2003b).

CONCLUSIONS

F0 discrimination of a group of high harmonics embedded in harmonics with fixed F0 can be affected by cues related to PPA (for cosine-phase stimuli) and by PDI. The learning effects found for such stimuli may partly reflect learning to make effective use of PPA and learning to overcome PDI.

F0 discrimination of a group of bandpass-filtered harmonics presented in TEN showed learning effects for LOW, MID, and MID-HIGH stimuli (harmonics 1-5, 11-15, or 14-18), but not for HIGH stimuli. The learning effects obtained with LOW, MID, or MID-HIGH stimuli transferred to other stimuli except HIGH (28-32). These results suggest that the underlying pitch mechanisms are similar for LOW, MID, and MID-HIGH stimuli, but that a different pitch mechanism operates for HIGH stimuli. We propose that LOW, MID, and MID-HIGH stimuli are discriminated using TFS information, while HIGH stimuli are discriminated using temporal envelope information.

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