20th International Congress on Sound & Vibration
ICSV20
Bangkok,Thailand
7-11 July 2013

INHERENT AND LEARNT ABILITIES FOR RELATIVE PITCH IN THE VIBROTACTILE DOMAIN USING THE FINGERTIP

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This paper reports experimental results concerning relative pitch discrimination. This is defined as the ability to distinguish one musical note as being higher or lower than another. Seventeen participants with normal hearing undertook a pitch discrimination experiment using the fingertip over a 16 session training period with a full baseline test before and after the training sessions. Two sinusoidal tones were presented, each of 1s duration separated by a 1s gap. A total of 24 tones were chosen to cover 12 intervals ranging from a semi-tone to an octave over the frequency range C3 to B4. The results show a high success rate for relative pitch discrimination with and without training. For intervals of 4 to 12 semitones, the success rates were >70% with or without the 16 training sessions. As a result of training, a significant improvement was found for individual intervals between 9 and 12 semitones when comparing the number of correct responses between pre-training and post-training tests. Comparison of pre- and post-training tests also showed an appreciable and significant improvement for the whole group of 12 intervals. In addition, reaction times to identify relative pitch tended to decrease over the training period.

1. Introduction

Ongoing research by the authors concerns the use and understanding of vibrotactile information to facilitate group performance for musicians with and without a hearing impairment. This study investigates the perception and learning of basic relative pitch (RP) in the vibrotactile mode via the fingertip. Subjective experiments are used to determine the extent to which participants can correctly identify and learn to distinguish the RP of two tones presented consecutively via vibration to the fingertip. RP is defined as the ability to distinguish one note as being higher or lower than another. The study also aims to identify the range of musical intervals for which RP can consistently be identified. It was hypothesized that an appreciable and significant improvement in RP can be obtained as a result of training.

2. Subjective experiment

2.1 Vibrotactile thresholds for the fingertip

For this RP experiment it is advantageous to choose a range of notes for which the average vibrotactile threshold is relatively flat so that all notes can be presented at a fixed level above threshold. Previous work by the authors[1] quantified the vibrotactile threshold on the pad of the distal phalanx of the middle finger for 31 participants with normal hearing. The participant's dominant hand rested upon the vibrating contactor. This was an aluminium disc with an area of 3.14cm^2 and a diameter of 2cm driven by an LDS V200 electrodynamic shaker. Eleven tones were presented as stimuli corresponding to the musical notes C and G in the range from C1 to C6. The frequencies were calculated using the ratio $2^{1/12}$ in twelve-tone equal temperament to give the frequency of the *n*th piano key relative to A4. The results are shown on Fig.1 and indicate a relatively flat region for the thresholds between C3 and C5.

This previous work[1] also assessed whether participants with normal hearing felt the onset and/or sustain of notes with a 1s duration when presented at threshold and 10dB above threshold. Results showed that onset awareness increases over the pitch range G4 to C6, being particularly evident from A5 upwards in this experiment. This has implications for the perception of pitch using vibration because detecting only the onset of a note will not give sufficient information to identify the note itself. For this reason it is appropriate to set a limit for the highest note to be considered in the RP experiment to A5.

Based on the above findings a total of 24 notes are used in the RP experiment to cover the entire range of notes between C3 (130.8Hz) and B4 (493.9Hz). This range represents one octave below and one octave above Middle C (C4).

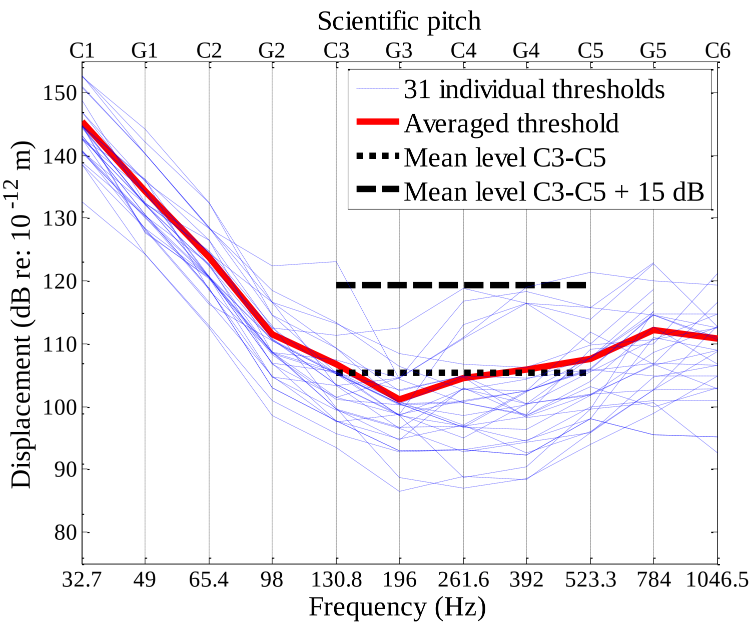

Figure 1. Vibrotactile thresholds for the pad of the distal phalanx of the middle finger for 31 normal hearing participants.

2.2 Experimental set-up

The experiment was carried out in a quiet room without visual distractions for the participants. The pad of the distal phalanx of the middle finger from the participant's dominant hand rested upon the same vibrating contactor used to establish the vibrotactile thresholds as described in section 2.1. The whorl, arch or loop of the fingerprint was positioned at the centre of the disc. Participants were instructed to relax and not to press down on the contactor. The contactor height was such that the middle finger rested upon it naturally. The experimental set-up is shown in Fig.2.

Masking noise was required to avoid unwanted audio cues due to sound radiated by the shaker and contactor. Previous work[1] indicated that bone conduction due to any occlusion effect from headphones does not affect the measured vibrotactile threshold; hence white noise was presented using headphones at a level of 78 dB L_{Aeq}.

Considering that the final application of vibrotactile technology is for performing musicians, it would be impractical for them to assess relative pitch at threshold values of vibration. For this reason, the presentation level for the stimuli was chosen to be 15dB above the average vibrotactile threshold between C3 and B4 (refer back to Fig.1). This was considered to be a comfortable level that avoids any adverse effects on participants from high vibration levels[2], and attempts to avoid the confounding factor of intensity affecting pitch perception[3,4].

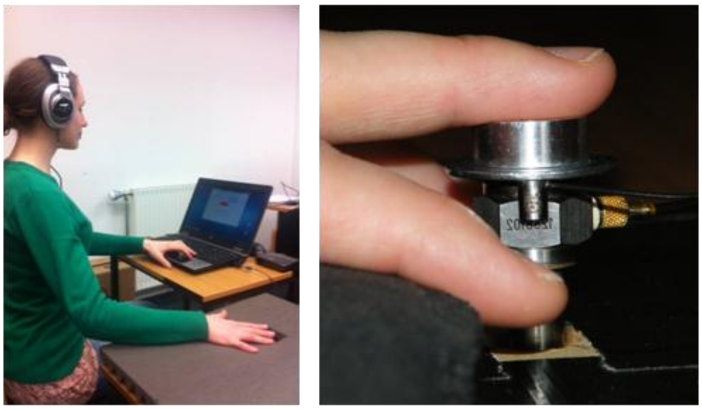

Figure 2. Experimental set-up (left) with detail of middle finger placed upon contactor (right).

2.3 Procedure

As with other studies on pitch perception[5,6] pairs of sinusoidal tones were presented consecutively. In this experiment, participants were asked ‘Is the second tone higher or lower than the first tone?’ in a two-alternative forced choice design.

In order to establish the participants’ ability to discriminate RP, both pre-training and post-training tests were administered without feedback on whether the participants’ responses were correct or incorrect. In each test a total of 420 interval pairs (i.e. two tones) were presented to the participant in random order. Each tone lasted for 1s with an interval between them of 1s. These interval pairs were ascending and descending in pitch and covered all 12 intervals ranging from a semi-tone to an octave over the frequency range C3 to B4.

After completing the pre-training test, participants completed 16 training sessions (one session per day) over a period of five to six weeks. In each training session 72 interval pairs were presented from the complete set of 420, comprising 6 permutations chosen randomly from each of the 12 possible intervals. However, once an interval pair was presented it was not used again in the same session or any following session until all possible pairs for that particular interval had been exhausted. To facilitate learning, feedback was given to the participant as to whether each answer was correct or incorrect. At the end of each training session, the participant was informed of the percentage answers that were correct, incorrect or unanswered. This procedure was implemented as a Matlab GUI to automate the presentation of stimuli and facilitate data collection.

The temperature of the fingertip was measured before and after each training session, and during each pre- and post-training tests using an infra-red thermometer. Based on the findings of

Verrillo and Bolanowski[7], the acceptable temperature range for valid measurements was chosen to be 24 to 36ºC.

2.4 Participants

Seventeen participants with normal hearing were recruited. All participants were healthy with no self-reported impairment of sensation in their hands. All participants were right handed, and carried out the experiment using the middle finger of the right hand. Participants consisted of 13 males and 4 females with an age range of 18 to 50 (μ: 27.7, σ: 9.5). Approval for all experiments was given by the Research Ethics Committees of the University of Liverpool and the Royal Northern College of Music.

3. Results

Statistical analysis was performed using either parametric (dependent *t*-tests) or non-parametric (Wilcoxon or Mann-Whitney) tests depending on whether or not the data was normally distributed. The distributions were assessed using the Shapiro-Wilk test.

3.1 Analysis of training sessions

The percentage figures for correct and incorrect responses at each interval size in semitones during the training sessions are shown in Fig.3. Only a small number of responses, ranging from 0.1 to 0.6%, were missing during training (this was similar to the number of missing responses in the pre- and post-training tests).

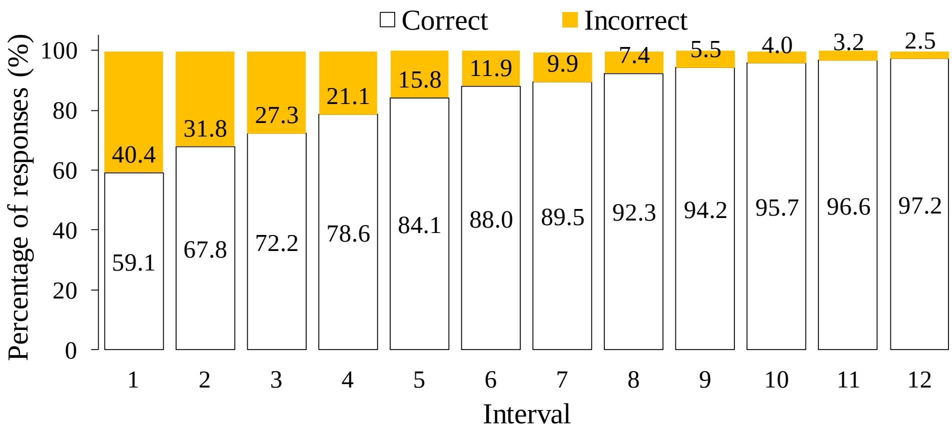

Figure 3. Correct and incorrect responses from all participants during the training period.

The percentage of mean correct responses from one training session to the next is shown in Fig.4. The results are shown for all participants as they were highly variable for individuals. When looking at all participants over the full set of 16 sessions, there was a general improvement but this trend was fairly weak (linear regression, R^2=0.452).

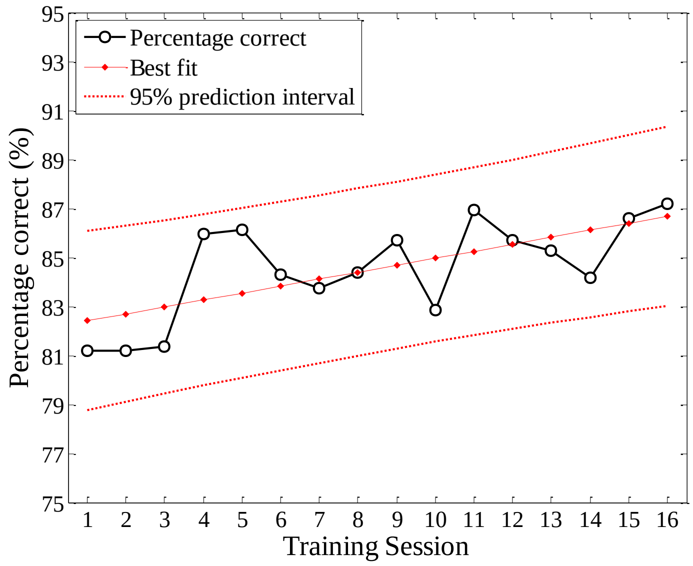

Figure 4. Percentage of mean correct responses in training sessions, straight-line fit and 95% prediction interval.

3.2 Analysis of pre- and post-training results

Figure 5 shows the percentage of mean correct responses from individual intervals for both pre-training and post-training. For intervals of 4 to 12 semitones, the results indicate high success rates (>70%) with or without the 16 training sessions. As expected, the larger intervals were easier to identify correctly than smaller intervals. For individual intervals between 9 and 12 semitones there was a significant improvement between pre- and post-training tests (Wilcoxon, $p<0.05$).

In both pre- and post-training tests there was a significant positive correlation ($p<0.001$) between both variables interval size and correct responses; as the interval size increased, the number of correct answers increased. The Spearman correlation coefficient between these variables increased from 0.664 in the pre-training test to 0.842 in the post-training test. This confirms that larger intervals are easier to distinguish than smaller intervals and that training is beneficial.

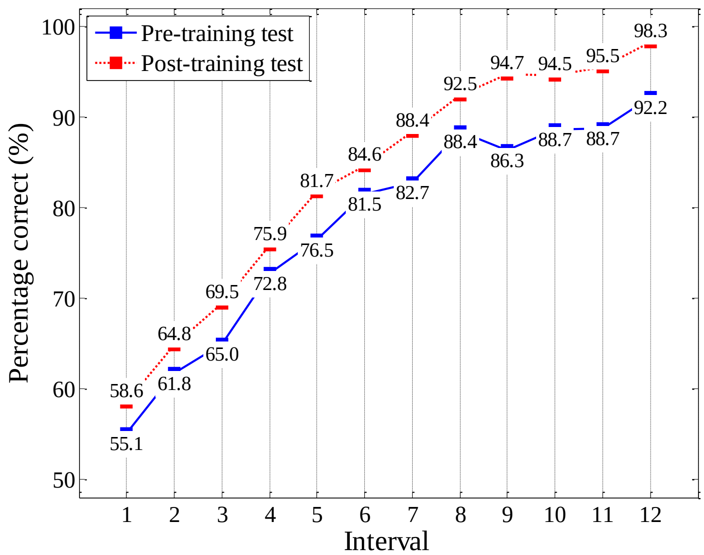

Figure 5. Comparison of mean correct responses from all participants in the pre- and post-training tests.

Figure 6 shows the results at each interval for pre- and post-training tests using box plots. The post-training test has a notably narrower spread of results than the pre-training test. This indicates that training helps bring participants up to a similar ability for all intervals except for one semitone (interval 1) and one tone (interval 2).

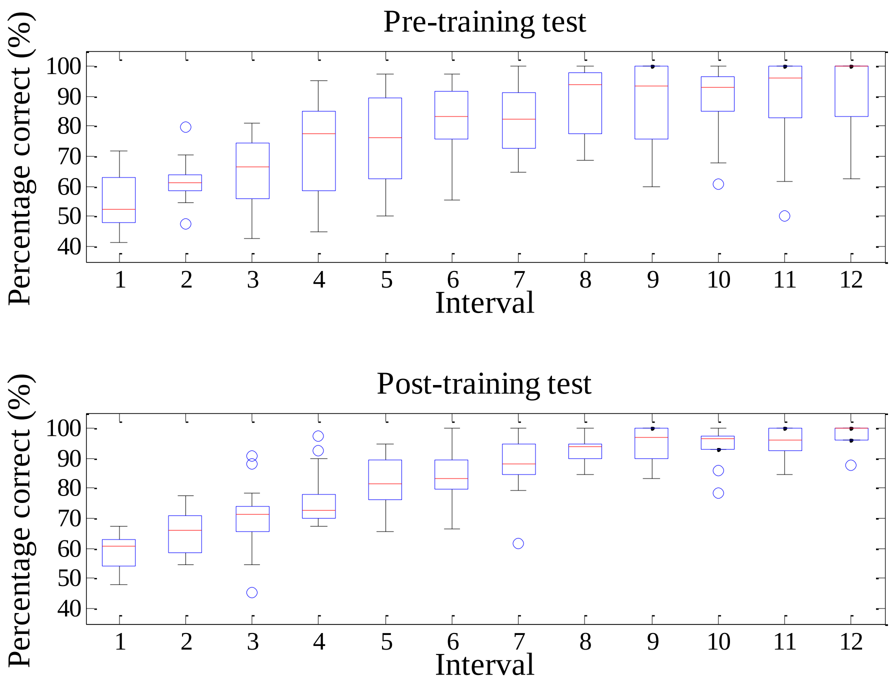

Figure 6. Box plots showing correct responses from all participants in pre- and post-training tests (circles are outliers).

Grouping the smaller intervals between 1 and 6 semitones also shows a significant improvement between pre- and post-training tests (dependent *t*-test, $p=0.001$). Grouping larger intervals between 7 and 12 semitones shows a larger improvement (Wilcoxon, $p<0.001$). As before this indicates that significant improvements in RP can be obtained as a result of training.

The Wilcoxon signed-rank test was used to consider the overall improvement at all intervals after training. The results show that the score of correct answers in the post-training test (median=87.5%) was significantly higher than in the pre-training test (median=80.3%), $T=3888.5$, $p<0.001$, $r=0.380$ (see Fig.7). The two medians are significantly different at the 5% significance level because their intervals do not overlap (NB interval endpoints are the extreme points of the notches.) The effect size, *r*, represents a medium-sized effect which supports the hypothesis that an appreciable significant improvement in RP can be obtained as a result of training.

Five participants (A, E, K, P and Q) showed a significant improvement between pre- and post-training tests (dependent *t*-test, $p<0.05$) with particularly strong improvement by participants A, E, and K (dependent *t*-test, $p<0.001$). The improvements at each interval are shown in Fig.8.

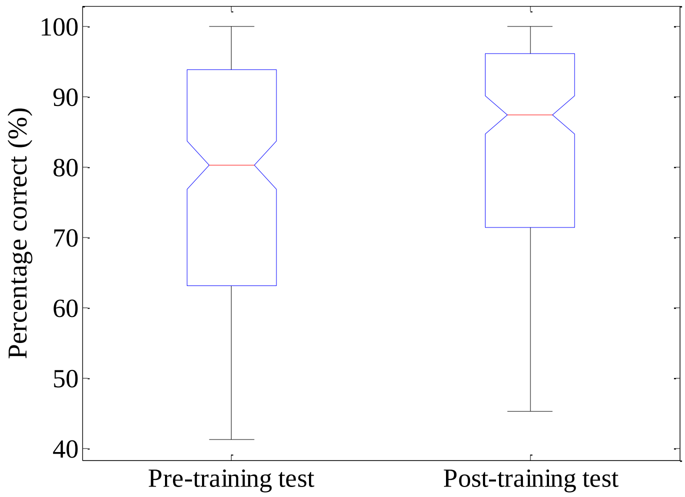

Figure 7. Box plots showing correct responses for all intervals and all participants in the pre- and post-training tests.

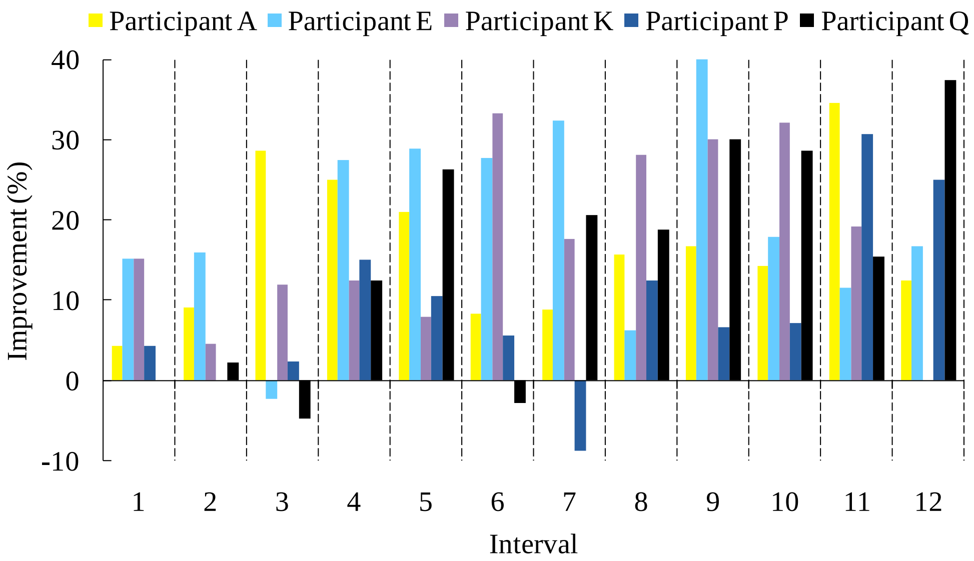

Figure 8. Improvement in RP between pre- and post-training tests for five participants.

3.3 Reaction times

Each participant had a 3s time window to respond to each question after an interval pair was presented. The measured reaction times are indicative of the participant's ability to make a decision and respond using the computer keyboard. The mean reaction time decreased over the training period and was faster by 0.18s after the sixteenth training session. There was a significant negative correlation (p<0.001) between training session and the mean reaction time due to the large dataset; however, the correlation is weak with a Spearman's correlation coefficient of 0.1. The difference between reaction times before and after training was not significantly different (Wilcoxon, p>0.05).

3.4 Comparison of pre-training tests with hearing impaired participants

Previous work[1] by the authors compared the vibrotactile thresholds on the pad of the distal phalanx of the middle finger from thirty-one participants who had normal hearing with eight participants who had a hearing impairment (profoundly or severely deaf). This showed no statistically significant difference between detection thresholds in these two groups. For the RP experiment it was only possible to have five hearing impaired participants (profoundly or severely deaf) carrying out the pre-training test. Analysis of these data shows that normal hearing participants were significantly better at identifying the relative pitch of two vibrotactile tones (median=80.3%) than hearing impaired participants (median=66.0%), U=4433.5, p<0.05. However this represented only a small effect, r=0.2; hence more hearing impaired participants would be needed to draw a stronger conclusion.

4. Conclusions

This experiment on relative pitch discrimination in the vibrotactile mode has been used to establish the musical intervals that can be consistently identified on the fingertip over a two-octave range of notes from C3 to B4. The results have shown a high success rate for RP discrimination with or without training and that larger pitch intervals are easier to identify correctly than smaller intervals; for intervals of 4 to 12 semitones, the success rates were >70% correct with or without the 16 training sessions.

As a result of training, it was found that there is a significant difference for individual intervals between 9 and 12 semitones comparing the number of correct responses between both pre-training test and post-training test. In addition, there was an appreciable and significant improvement for the whole group of 12 intervals comparing pre- and post-training tests. It was also shown that reaction times to identify relative pitch tended to reduce over the training period. Using only the pre-training test it was shown that normal hearing participants were significantly better at identifying the relative pitch of two vibrotactile tones than severely or profoundly deaf participants; however, more participants are needed to draw more robust conclusions. Further work will explore the degree to which cognition of vibrotactile pitch can be relative and/or absolute on fingertips and feet.

Acknowledgements

The research project entitled ‘Interactive performance for musicians with a hearing impairment’ No. AH/H008926/1 is funded by the UK Arts and Humanities Research Council (AHRC).

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