Technical Report

Implementation of a fast method for measuring psychophysical tuning curves

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Abstract

Objective: To implement a fast method for measuring psychophysical tuning curves (PTCs) for use in clinical applications, such as assessment of frequency selectivity and detection of dead regions in the cochlea. Design: The method is based on that described by Sek et al (2005) and has been implemented in software that can be run on a PC with a good-quality sound card. In addition to the main narrowband noise masker, a lowpass noise masker can be generated to prevent detection of a distortion band corresponding to the simple difference tone. Results: The software includes a routine for measuring the absolute threshold at the signal frequency and includes methods for estimating the frequency at the tip of the PTC. A PTC can typically be determined in about three minutes. A small amount of practice (two to three runs) may be required to achieve stable results. Conclusions: The software implementation allows PTCs to be measured quickly without a requirement for specialised equipment.

Key Words: Psychophysical tuning curves; Frequency selectivity; Dead regions

The psychophysical tuning curve (PTC) is a well known measure of the frequency selectivity of the auditory system (Chistovich, 1957; Small, 1959; Moore, 2003). To measure a PTC, the sinusoidal signal is fixed in frequency and presented at a fixed (usually low) sensation level (SL). A narrowband noise is usually used as the masker to avoid a strong influence of beat detection on the results (Moore et al, 1998; Kluk & Moore, 2004). For each of several masker centre frequencies, the level of the masker required just to mask the signal is determined. For normally-hearing participants, the tip of the PTC (i.e. the frequency at which the masker level is lowest) lies close to the signal frequency (Vogten, 1974; Moore, 1978). When plotted on a logarithmic frequency scale, PTCs usually have steep slopes adjacent to the tip and a shallower low-frequency ‘tail’. For participants with cochlear hearing loss, PTCs are usually broader, and sometimes lack the sharp tip (Hoekstra & Ritsma, 1977; Zwicker & Schorn, 1978; Kluk & Moore, 2005). When a hearing-impaired person has a dead region in the cochlea at the signal frequency (a region where the inner hair cells and/or neurons are functioning very poorly, if at all), the tip of the PTC may be shifted away from the signal frequency (Thornton & Abbas, 1980; Turner et al, 1983; Florentine & Houtsma, 1983; Moore et al, 2000; Moore & Alcántara, 2001; Kluk & Moore, 2005, 2006).

PTCs may be useful as a general diagnostic tool (Zwicker & Schorn, 1978) and specifically for the diagnosis of dead regions in the cochlea and estimation of their edge frequencies (Moore et al, 2000; Moore & Alcántara, 2001; Kluk & Moore, 2005, 2006). However, measurement of PTCs in the traditional way, by estimating the masker level required for threshold for several masker centre frequencies, is time-consuming and therefore impractical in clinical situations. Several researchers have proposed the use of a faster method, based on Békésy tracking (Zwicker, 1974; Summers et al, 2003; Sek et al, 2005). For the method described by Sek et al (2005), the masker is a band of noise that is slowly swept in frequency, either upwards or downwards. The signal is pulsed on and off repeatedly while the masker is continuous; this helps to draw attention to the signal. The masker level is initially below that required to hear the signal. The masker level is increased when the participant indicates that the signal can be heard, and decreased when it is not. In this way, the masker level tracks the level required for threshold. Sek et al (2005) showed that PTCs obtained using their
method showed good repeatability and corresponded well with PTCs obtained in the traditional way.

Until now, this method required specialized equipment for its implementation. Here, we describe a software implementation of the method of Sek et al (2005) which can be run on a PC equipped with a good-quality sound card and headphones. Each ear is tested separately (the ear to be tested is selected in the software). If required, an external amplifier can be used between the sound card and the headphones. The software is called SWPTC (SW stands for sweeping).

Implementation

Hardware and software requirements
The SWPTC software can be run on a 32-bit PC using Windows XP (Service Pack 3 or later), Windows Vista, or Windows 7. The software automatically detects what operating system is used. The software can be used with either a 16- or 24-bit sound card. The achievable dynamic range is 90 dB for a 16-bit card and 100 dB for a 24-bit card; these ranges are slightly lower than the theoretical ranges due to limitations in DIRECTX which is a collection of application programming interfaces that form part of the Windows operating system. The sampling rate used is 22050 Hz, which means that the highest frequency that can be generated is approximately 10000 Hz.

Calibration of levels
In order to set levels accurately, two pieces of information are requested by the software:

1. The sensitivity of the headphones used, specified as the sound level in dB SPL produced for an input of 1 volt RMS (usually at a frequency of 1000 Hz). This can often be found in the manufacturer’s specifications.

2. The voltage generated at the input to the headphones by a full-scale sine wave (using the full digital range of the sound card). The software generates such a full-scale sine wave on both channels of the sound card when the ‘Calibrate’ button is pressed. Pressing this button also causes a panel to appear that indicates the settings of volume control sliders, including the ‘Master’ volume control and the ‘Wave’ volume control. These can be used to increase or decrease the output voltage. The volume control should be measured with a voltmeter or other suitable device such as an oscilloscope or spectrum analyser and entered into the SWPTC software.

Once the two calibration values have been entered, they are saved. The range of levels available (the lowest and the highest levels that can be generated for a sine wave) are indicated by the software when the two calibration values described above have been entered. If these ranges are unsuitable for the intended application, the calibration procedure should be repeated and the volume controls should be used to adjust the output level.

Warning sounds
To make measurements using SWPTC, it may be necessary to set the system output volume relatively high. In that case, auditory warning signals generated by Windows, or generated during the operation of SWPTC, may be rather loud. The software requires that these warnings be turned off, to avoid startling the participant. When the SWPTC software is started, it checks whether the Windows warning sounds are active. If they are, a message is displayed indicating how to turn the warning sounds off. Once the warning sounds are turned off, the SWPTC software must be restarted.

Task
The task is to detect a sinusoidal signal, which is pulsed on and off (by default 200 ms on and 200 ms off, but values can be changed in the software), in the presence of a continuous noise masker whose centre frequency slowly changes, from low to high (Forward sweep), or from high to low (Reverse sweep). The signal frequency and level can be selected in the software. It is recommended that the signal is set to a level of 10 dB SL. The software includes a facility for estimating the absolute threshold at the signal frequency (see below for details).

The direction of the sweep, the starting and ending frequencies of the sweep, the masker bandwidth, the initial masker level, and the rate of change of masker level can all be selected in the software. This is illustrated by the screen shot shown in Figure 1. Initially, the signal is presented without any masker, so that the participant knows ‘what to listen for’. Then the masker is presented, preferably at a low level so the signal remains audible. The participant is requested (via a box on the screen) to press and hold down the space bar when the signal is audible. While the space bar is pressed, the masker level is increased (at a rate that can be specified in the software; the default value is 2 dB/s). The participant is requested to release the space bar when the signal is not audible. While the space bar is not pressed, the masker level is decreased. In this way, the masker level ‘tracks’ the level required just to mask the signal. A run can be interrupted at any time by clicking on a ‘button’ on the screen labelled ‘Stop’.

If the output level limitations of the system are reached during a run, a box on the screen becomes red to indicate this. The masker level is then held at the maximum permitted by the system. Usually this does not affect the estimate of the frequency at the tip of the PTC, although it may affect the ‘skirts’ of the PTC.

Display of results
At the end of a run a graph is displayed of the level of the noise as a function of the centre frequency of the noise. A running average of this level is also shown. The masker level and centre frequency at the tip of the PTC are automatically estimated and are displayed on the screen. All data are saved on the hard disk of the PC.

Abbreviations

DLF Double low-pass filtering
PC Personal computer
PTC Psychophysical tuning curve
RMS Root mean square
ROEX Rounded exponential
SL Sensation level
SWPTC Sweeping PTC
TPMA Two-point moving average

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Hysteresis effect
The use of a sweeping masker can lead to a hysteresis effect described in Sek et al (2005). The frequency at the tip of the PTC is slightly higher for a Forward sweep than for a Reverse sweep. Hence, for a given signal frequency, it is advisable to measure the PTC using both a Forward sweep and a Reverse sweep, and to average the tip frequencies obtained for the two cases.

Measurement of absolute threshold
The software provides the option of measuring the absolute threshold of a sinewave signal at the specified signal frequency. This option is recommended so as to achieve the correct signal presentation level. The starting level of the signal can be set in the software. It is recommended that this level should be at least 10 dB above the anticipated absolute threshold. An adaptive two-alternative forced-choice procedure with a two-up one-down adaptive rule (Levitt, 1971) is used to measure the absolute threshold. The participant responds by ‘clicking’ on virtual buttons on the PC screen, as illustrated by the screen shot in Figure 2. Feedback is provided by flashing the button that was pressed, using a green flash for correct and a red flash for wrong. The resulting threshold value is shown on the screen, together with the recommended signal level for measurement of the PTC.

Low-pass noise
If the participant has relatively good hearing at low frequencies (40 dB HL or better) with poorer hearing at high frequencies, the outcome of the test can be influenced by the detection of a combination band (centred at the difference in frequency between the signal and masker) produced by the interaction of the signal and masker (Moore & Alcántara, 2001; Moore, 2004; Kluk & Moore, 2005). For example, if the signal frequency is 2000 Hz and the masker centre frequency is 1800 Hz, a combination band centered at 200 Hz may be produced. The participant may hear this band, without hearing the signal itself, if hearing is good at 200 Hz. To prevent this combination band from being used as a detection cue, the option is provided of adding a continuous low-pass noise to the main (sweeping) masker. The cutoff frequency and overall level

![Figure 1](image1.png)

**Figure 1.** Screen shot (colour removed) showing part of the ‘page’ on which measurement parameters are entered.

![Figure 2](image2.png)

**Figure 2.** Screen shot (colour removed) showing part of the display during measurement of an absolute threshold.
of the low-pass noise can be selected in the software. It is recommended that these are chosen as follows:

1. The cutoff frequency is selected to correspond to the frequency at which the hearing loss reaches 40 dB HL (using interpolation where necessary). This recommendation is based on the findings of Moore and Alcantara (2001) and Kluk and Moore (2005), which showed that the combination band was not audible when the hearing loss in the frequency region of the band was more than 40 dB. The cutoff frequency of the lowpass noise should be at least one octave below the signal frequency to avoid the noise having a direct masking effect on the signal (Moore et al, 1997).

2. The overall noise level is set to be about 40 dB below the signal level. For example, if the signal level is 85 dB SPL, the overall noise level is set to 45 dB SPL. This recommendation is based on the data of Plomp (1965) showing that the level of the combination tone (corresponding to a simple difference tone) is at least 40 dB below the level of the primary tones. A noise with a level equal to or above the expected level of the combination band, and falling in the same frequency region, should be effective in masking the combination band (Moore et al, 1997).

**Estimation of tip frequency**

The software offers several methods for estimating the frequency at the tip of the PTC (and the sharpness of tuning of the PTC). These are all based on the means of successive turn points in masker level, which is referred to as the two-point moving average (TPMA). An initial estimate of the tip frequency is taken as the frequency at which the masker level is lowest, based on the TPMA. This initial estimate is used to determine which points fall on the low side and which points fall on the high side of the PTC. The methods for estimating the tip frequency are illustrated in Figure 3, which shows a fast PTC obtained from a participant with normal hearing, using a signal frequency of 2000 Hz, a masker bandwidth of 200 Hz and a rate of change of masker level of 2 dB/s. The methods are:

1. Double regression: straight lines are fitted separately to the lower and upper sides of the PTC (excluding the region immediately adjacent to the initial estimate of the tip frequency and the shallower part of the low-frequency tail) and the tip frequency is estimated from the intersection point of the two lines (top-left panel).

2. Moving average: the data are smoothed with a two-point or four-point moving average, and the frequency corresponding

![Figure 3](image-url)
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The TPMA is shown as a thin line in the upper panels of Figure 3 (the four-point moving average is not shown).

3. The data in the region around the tip are fitted with a quadratic function, and the frequency corresponding to the minimum of the quadratic function is taken as the tip frequency (top-right panel).

4. The data are lowpass filtered and the frequency corresponding to the minimum of the result is taken as the tip frequency. The lowpass filtering procedure is similar to the FiltFilt.m procedure in Matlab. The data are passed through the lowpass filter, the output is reversed and the resulting data are filtered again using the same lowpass filter. Finally, the output from the second filtering stage is reversed again. This double lowpass filtering (DLF) effectively removes any phase shifts produced by the filter, which leads to an unbiased estimate of the tip frequency (bottom-left panel).

5. Each side of the PTC is fitted with a rounded-exponential function (Patterson et al., 1982), and the intersection point of the two functions is taken as the tip frequency (bottom-right panel).

If the number of turnpoints above and below the tip of the PTC is not sufficient for a given method to be applied, the software gives a warning to that effect. It is not possible to state definitively which method is ‘best’ in general; which method works best for a given PTC depends on how many turnpoints there are, whether there are several turnpoints both above and below the tip frequency, and whether the PTC shows a reasonably regular V shape, or is more irregular in form. Visual inspection of the obtained PTC and the fitted function can be used to pick the method that is appropriate for a given PTC. For PTCs that have a reasonably regular V shape, the different methods usually lead to estimates of the tip frequency that cover a range of about ±10% around the mean estimate. However, when the PTC is irregular in shape, or has a very shallow slope on one or both sides, the estimates of the tip frequency often vary over a wide range.

Example Results

Figure 4 shows examples of fast PTCs obtained from a participant with a severe hearing loss that was greater at high frequencies than at low frequencies. The 800-Hz signal was presented at 86 dB SPL, corresponding to 10 dB SL. The masker bandwidth was 160 Hz. For the PTC in the upper panel, the masker frequency was swept from 400 to 1200 Hz over a duration of 180 s (Forward sweep). For the PTC in the lower panel, the masker frequency was swept from 1200 to 400 Hz over the same duration (Reverse sweep). The masker level was changed at a rate of 1 dB/s. The jagged dashed lines show the masker levels visited. The smoother continuous lines show the means of successive pairs of turn points. For both PTCs, the tip is clearly shifted below the signal frequency of 800 Hz. The tip frequency was about 665 Hz for the Forward sweep and 595 Hz for the Reverse sweep; this reflects the hysteresis effect described above. The ‘true’ tip frequency can be estimated as the mean of the tip frequencies for the two cases, namely 630 Hz. Since the tip of the PTC was shifted well below the signal frequency, the results suggest that the participant had a dead region with an edge frequency of about 630 Hz and extending upwards from 630 Hz.

We have found that most participants are able to perform the task reasonably reliably, although, especially for elderly participants, two or three practice runs may be required to achieve stable results. Sometimes, the tip of the PTC is very broad, making it difficult to estimate the tip frequency.

Obtaining the software


Instructions for installing and running the SWPTC software

This program will run under Windows XP (Service pack 3 or later), Windows Vista, and Windows 7.

Unzip the files to a directory of your choice. The three files should be in the same directory.

Close all programs.
Using “Windows Explorer” click on the file setup.exe. Follow the instructions on the screen. This should install the software. An icon labelled SWPTC, looking like a folder, should be placed on your screen.

If you click on this, you should see two entries:

SWPTC data - this is where the results are stored
SWPTC - click on this to run the program

When the program is running, click on “Settings” to perform initial calibration of levels.

Two pieces of information are needed:

1) The sensitivity of the headphones used, specified as the sound level in dB SPL produced for an input of 1 volt RMS (usually at a frequency of 1000 Hz). This can often be found in the manufacturer’s specifications. The default value is 95 dB SPL for 1 volt RMS. The number appropriate for your headphones can be entered in the box.

2) The voltage generated at the input to the headphones by a full-scale sinewave (one using the full range of the sound card). The software will generate such a full-scale sinewave when you press the “Calibrate” button. Measure the RMS voltage at the input to the headphones and enter the voltage in the appropriate box.

To measure PTCs using the software, it may be necessary to set the system output volume relatively high. In that case, auditory warning signals generated by Windows, or generated during the operation of the software, may be rather loud. It is recommended that these warnings be turned off, to avoid startling the client. To turn off the auditory warnings, click on:

Start > Control panel > Sounds and audio devices
Select the tab marked “Sounds” and under “Sound schemes” select “No sounds”. Then click on “Apply”.

Click on “Help” in the main menu for more detailed information. Please send any comments or suggestions to one of us.

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References


Supplementary material available online