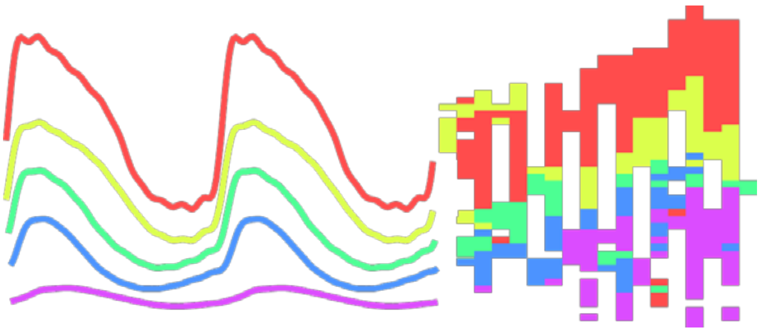


The FonaDyn Handbook

Sten Ternström

with Dennis Johansson and Andreas Selamtzis

Dept. of Speech, Music and Hearing
School of Computer Science and Communication
KTH Royal Institute of Technology
SE-100 44 Stockholm, Sweden

Disclaimer: FonaDyn and its supporting materials are provided to the public domain, free of charge and with no commitment to further support. Much effort has been invested in the development, and the code has no risky aspects that we are aware of. Still, all software is likely to have errors of one kind or another. We are of course interested in learning of any bugs that you might come across.

You may install, run or modify FonaDyn only if you agree that you will not hold the authors S.T., D.J. and A.S. responsible for any loss of data or function that may be incurred as a consequence of installing or using FonaDyn.

Mandatory citation: publications of any research that you perform using FonaDyn or any derivative thereof must cite the following article:

Ternström S, Johansson D, Selamtzis A (2018). FonaDyn - a system for real-time analysis of the electroglottogram, over the voice range. *SoftwareX* vol(no), year, pages.

FonaDyn version: 1.5.0

Contents

0 Overview

The FonaDyn program is a research tool for investigating the waveform of the electroglottographic signal (EGG), over the entire voice range. It gives real-time visual feedback of phonation types, mapped into a voice range profile (VRP) [1]. Different EGG waveshapes are automatically categorised and assigned to layers of different colours in the VRP. ‘Phonation types’ may refer to modal/falsetto, or to any other types of phonatory differences, including gradings within a single voice register. FonaDyn can be used to pursue many kinds of research questions on phonation, voice source dynamics, source-filter interaction and effects of training and/or therapy. The only constraint is that the phonation must be reasonably periodic throughout. Of course, the researcher needs to understand in some detail how FonaDyn works, and how to use it. That is the main goal of this handbook.

FonaDyn uses a simple form of ‘machine learning’, by which different EGG pulse shapes are automatically classified into ‘clusters’. The learning feature has several important advantages. The categories need not be known in advance, rather, FonaDyn helps you to find them. The classification does not initially rely on any prescribed thresholds, but rather emerges from the data. With a careful choice of the clustering parameters, it is possible to produce a classification or stratification of the EGG that is specific to the research question at hand.

FonaDyn also implements a novel way of detecting phonatory breaks and instabilities, using the so-called ‘sample entropy’, as applied to cycle-by-cycle metrics. In moderate to loud phonation, this metric stays at zero except when something sudden happens, such as a voice break.

FonaDyn is not a stand-alone application. It is run from within the SuperCollider system, which must be installed first. SuperCollider is a free open-source software development tool that runs on MacOS, Windows and Linux. It was originally developed by James McCartney for the computer music community.

For the hardware, you will need a reasonably modern computer, a high-end digital audio interface, a good microphone, an electroglottography system with an analog line output, and a quiet room in which to record. SuperCollider can use any Windows- or Mac-compatible audio interface, but not laboratory data acquisition boards. With some optional hardware, it is nevertheless possible to acquire also non-audio signals, in parallel and in synchrony with the voice and EGG signals.

This book has three parts:

- Part 1 describes how to get started with FonaDyn: the installation and the hardware requirements.
- Part 2 describes the theory and design choices underlying FonaDyn.
- Part 3 describes the user interface and the most common handling procedures.

1 PART ONE - Getting started

1.1 Hardware requirements

- A low-noise microphone at a fixed distance from the mouth. It is important to verify that no audible hum, hiss or other extraneous sound is present, by listening at high gain.
- A high-end digital audio interface that can be configured to have a microphone signal on the first input and a line-level signal on the second input. We recommend the RME line of USB/Firewire audio interfaces, see www.rme-audio.com. Others may work just as well.
- An electroglottograph. Note that this handbook does *not* cover the use of your EGG device as such. Please observe its instructions carefully, for how it must be powered, maintained and connected for use. Some devices deteriorate quickly if overcharged, resulting in higher EGG noise levels.
- A high-performance computer running Windows 7 or higher, or Apple Macintosh running OSX. The screen resolution needs to be at least 1200× 800 pixels. It can be convenient to have two display screens, since other programs will often be used at the same time.
- For prompting of the subject, closed circumaural headphones.
- For parallel acquisition of non-audio signals, such as aerodynamic data, see section 3.2.7.

1.2 Software setup

IMPORTANT: If your computer is centrally managed by an IT department, there are several things that they have to know about, in order to install SuperCollider and FonaDyn in a useable way. These are listed in section 1.2.6.

If you have not already done so, you will need to install the driver and control software that came with your digital audio interface or sound card, and become reasonably familiar with it.

Then install SuperCollider on your system, as described below. Once you have installed SuperCollider itself, you should probably play around with it a bit, if only to learn how to run anything at all. You need to know at least how to evaluate a line of SuperCollider code, so that you can install and start FonaDyn. There is a good Help system built into SuperCollider. There is also a separate website at doc.sccode.org that you can read from anywhere, with the same content.

Installing FonaDyn also installs a number of FonaDyn-specific files into the Help system. These are will be of interest mostly if you are interested in *how* the FonaDyn software works, under the hood.

1.2.1 Versions of SuperCollider

SuperCollider is maintained by an active community of voluntary developers. New versions are released about once a year. There are versions for the major operating systems, and also in some cases separate 32-bit and 64-bit versions. From the user's perspective, there is little or no difference between them.

FonaDyn 1.5.0 is built to run with the 32-bit version of SuperCollider 3.8.0. It has been developed on Windows and tested on MacOS.

In January 2018, the community released a newer version, SuperCollider 3.9.0. This version introduces a different format for the plug-in executables, which means that the FonaDyn-specific plug-ins in version 1.5.0 will *not* run with SuperCollider 3.9.0. Therefore you should follow the installation instructions carefully, and download the previous version 3.8.0 of SuperCollider and the sc3-plugins.

A later version of FonaDyn will be compatible with the newer format (but not with the old format), and its plugins will 64-bit. Later versions will not run on 32-bit operating systems, which by now are rather old.

1.2.2 Windows 7 and higher

Checking for common libraries

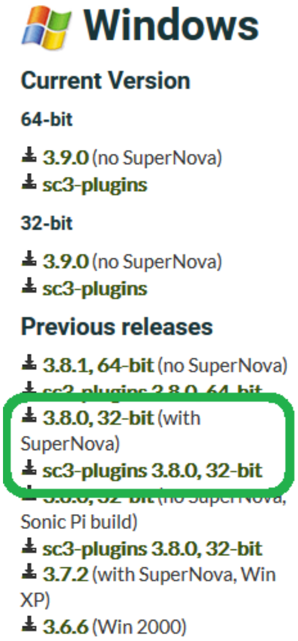
Run the Windows Control Panel, and find the list of installed programs. Look for this component: “Microsoft Visual C++ 2015 Redistributable (x86)”. If it is not there, you may need to install it; and in any case, it does no harm to do so. The download can be found at

https://www.microsoft.com/en-us/download/details.aspx?id=48145 .

Download and run the file **vc_redist.x86.exe**.

Installing SuperCollider 3.8.0

1. Visit the SC download web page [2] and download the following two components (framed in green):



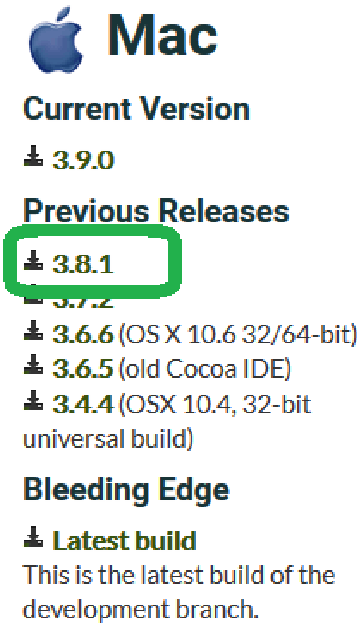
2. Install SuperCollider 3.8.0, by running the downloaded .EXE file.

3. In the **sc3-plugins** .ZIP archive, read the README file, to choose the right location. Then install the sc3-plugins, by extracting the other contents of the downloaded .ZIP file into the appropriate Extensions directory. We recommend that you install the sc3-plugins into the directory for all users. On recent versions of Windows, this will be the directory `C:\ProgramData\SuperCollider\Extensions`.

1.2.3 Mac OSX

Installing SuperCollider 3.8.1

1. Visit [the SC web download page][2]. Download the following:



This will download a zip file that contains the Mac installer package and some README files. Read them.

2. For getting the sc3-plugins, go to this page:

https://github.com/supercollider/sc3-plugins/releases

and download the zip file **sc3-plugins_OSX_SC3.8_692f92f.zip**.
You can click on this link to access that file:

https://github.com/supercollider/sc3-plugins/releases/download/Version-3.8.0/sc3-plugins_OSX_SC3.8_692f92f.zip

3. In the **sc3-plugins** .ZIP archive, read the README file, to choose the right location. Then install the sc3-plugins, by extracting the other contents of the downloaded .ZIP file into the appropriate Extensions directory. We recommend that you install the sc3-plugins into the directory for all users. On recent versions of OSX, this is
`/Library/Application Support/SuperCollider/Extensions.`

1.2.4 Linux

There is a Linux distribution for SuperCollider [2], but, as is customary with Linux, it is provided in source code form only. This means that you have to download the whole source and compile SuperCollider itself, before you can install FonaDyn on Linux. Experience of making such builds will be necessary. You will need to find version 3.8.0 in the Releases link at supercollider.github.io/download. We have compiled the platform-specific plug-in files (provided, but not yet tested), for those who might wish to try getting it up and running.

1.2.5 Installing FonaDyn into SC

1. Download **FonaDynInstall-*version*.zip** using the download link that you have obtained directly from us.

2. The directory **FonaDyn Extras** in FonaDynInstall-*version*.zip contains some useful files that are not SuperCollider code. Unzip and store them wherever you like.

3. Unzip the contained directories FonaDyn and FonaDynTools into an Extensions directory. We recommend that you put them into your own SuperCollider User Extensions directory. On recent versions of Windows, this will be `C:\Users\<username>\AppData\Local\SuperCollider\Extensions`.

   On OSX, this will be the directory
   `/Users/<username>/Library/Application Support/SuperCollider/Extensions`.

4. (Only on Mac OSX:) Using the Macintosh Finder, manually copy the file
   `…/FonaDynTools/osx/libfftw3f.3.dylib`
   to the system folder
   `/usr/local/lib`
   You will need to supply authorization for this operation, which is why the installation script can't do it.

5. (Re-)start SuperCollider. Wait for the "Post window" to display this line:

   ```
   *** Welcome to SuperCollider 3.8.0. *** For help press Ctrl-D.
   ```

6. In a new code window (**File** | **New** or Ctrl+N), type and then evaluate the line

   ```
   FonaDyn.install;
   ```

   This will perform a few checks, and copy a few additional files to their proper locations. You should now be able to start FonaDyn, by evaluating the line

   ```
   FonaDyn.run;
   ```

7. If the installation appears to have failed, or you change your mind, you can delete only the FonaDyn folders (no questions asked!) by evaluating the line

```
FonaDyn.uninstall;
```

The FonaDyn directory contains source code and Help files that are specific to FonaDyn. You can read these help files using the built-in SuperCollider help system, under “Browse | FonaDyn”.

The FonaDynTools directory contains supporting code that was written for FonaDyn, and may be of interest also to other SC developers. You can read these help files similarly, under “Browse | Tools”. The FonaDynTools directory also contains three subfolders with the platform-specific compilations of the FonaDyn UGens. The C++ source code for these UGens is not included, but can be provided upon request.

1.2.6 Audio device configuration

FonaDyn requires one stereo pair in and one stereo pair out. If your system’s default audio device has only two inputs and outputs, then these are what FonaDyn will use. If you are using an external multichannel audio interface (recommended), then your operating system will probably list more than one pair of inputs and one pair of outputs. FonaDyn will use the first pair of inputs and the first pair of outputs. It can be configured (in the program code) to record and play on any combination of multiple inputs and outputs, provided that they all sit on the same audio interface hardware (or on separate, but electrically synchronized devices). A list of currently available audio devices is printed in the Post window whenever the server process SCSYNTH is booted.

If you will not be using SuperCollider for anything else, you can specify 2 ins and 2 outs in the SC startup file. For instructions on how to do this, see the SC documentation for the startup file. The startup file has its own entry in the **File** menu of SCIDE, so it is easy to find. Activating more ins and outs than are needed may incur some unnecessary CPU load.

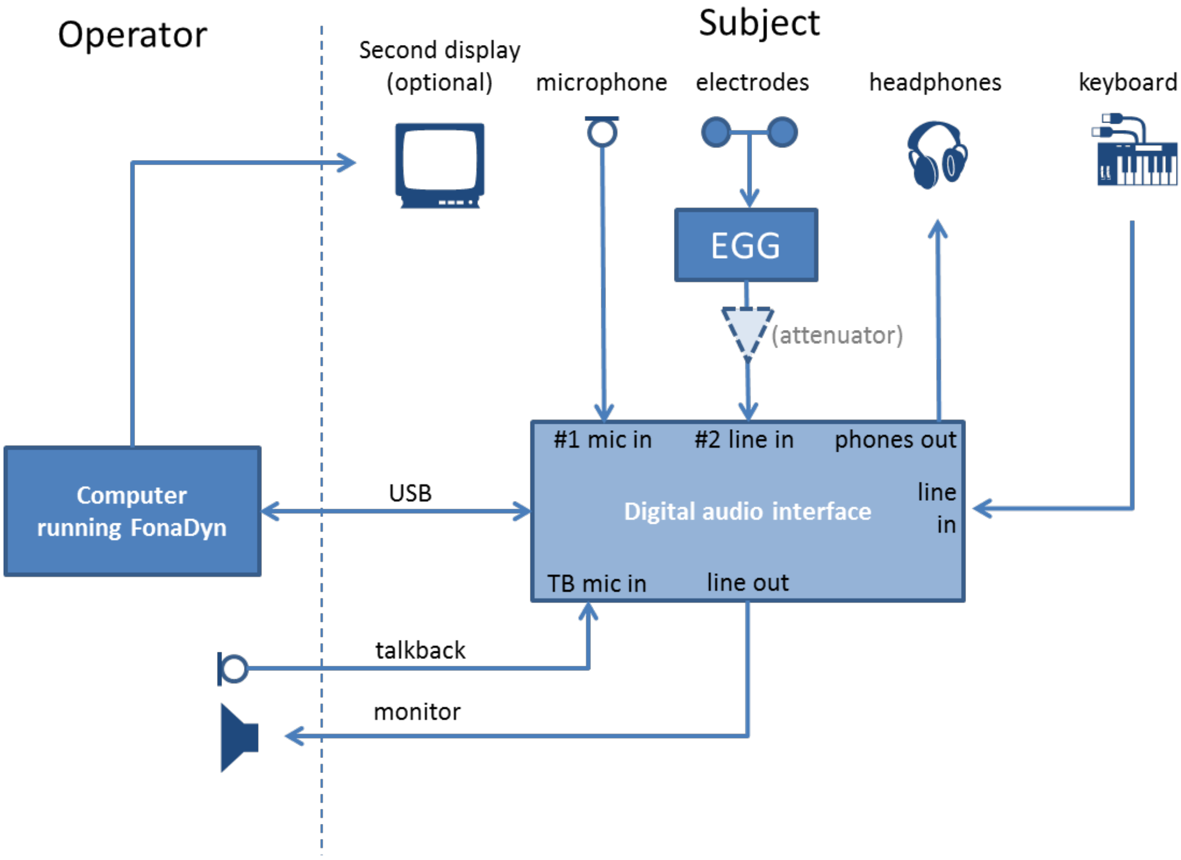


Figure 1. Typical recording setup.

A typical experimental setup is shown in Figure 1. The first (left) input channel must receive the signal from a microphone, via a microphone preamplifier. Many audio interfaces have built-in microphone preamps, on two or four inputs.

The second (right) input channel must receive the line-level signal from the electroglottograph. Unlike the microphone signal, the EGG signal level does not need to be calibrated. Howver, it should be adjusted so as to prevent clipping. Note that some EGG devices have a large voltage swing on their outputs, typically ±10 volts, which is too strong for most audio interfaces. If the EGG device's output level cannot be turned down enough, you may need to pass it via an attenuator to the audio interface. If your audio interface has adjustable input sensitivity, choose the *least* sensitive setting for the EGG signal.

1.2.7 Centrally managed installation

If your computer is centrally managed, it may have access policies in effect that will stop SuperCollider from doing certain things. Please show this section 1.2 of the handbook to your IT-support department, so that they can install SuperCollider with the necessary privileges, etc. Have them note especially the following:

SuperCollider is a software development environment in which it is necessary for users to be able to create/modify files in certain privileged locations and/or functions. At run-time, it does real-time processing of audio files, which needs to be fast, while being harmless from a malware point of view.

In Windows, the easiest thing is usually to install SuperCollider not under Program Files (x86) but in some directory directly under C:, for example C:\SuperCollider\, and properly set Access Control Lists (ACL) to allow users to change files within this directory. This will allow any user to edit the important configuration file **startup.scd**, for example.

There are three Win32 **.exe** modules: **scsynth.exe**, **sclang.exe** and **scide.exe**, which communicate with each other using a network protocol, and they must be allowed to do so. For performance reasons, it may also be necessary to include their processes in the list of processes that are excepted from anti-virus monitoring.

For its signal processing functions, SuperCollider uses a large number of small DLL's that have the filename extension .SCX . On rare occasions it may happen that an anti-virus program will quarantine one of these, causing SuperCollider to complain that a particular module is not found. We have never known this actually to be malign, but of course your policies must be upheld. You will have to decide what to do about it.

On Windows, the libraries used by SuperCollider require the **Microsoft Visual C++ 2015 Redistributable (x86)**; and the FonaDyn program needs a **pthreadGC2.dll** installed into the same directory as **scsynth.exe**. This latter copy operation is attempted by the FonaDyn installation script (**FonaDyn.sc**), but it may fail if the user is not authorized.

On Mac OSX, there is a library in FonaDynInstall.zip/FonaDynTools/osx **libfftw3f.3.dylib** which needs to be copied into /usr/local/lib. This copy operation is attempted by the FonDyn installation script (**FonaDyn.sc**), but it may fail if the user is not authorized.

2 PART TWO - Theory

2.1 Introduction

The underlying ideas were first described by Selamtzis and Ternström [3]. The input EGG signal is first segmented into individual cycles, each of which is analysed with the Discrete Fourier Transform. The resulting harmonic magnitudes and phases are then input to a so-called K-means clustering algorithm. This algorithm treats the data as point coordinates in a high-dimensional space, and allocates each point to the cluster whose centroid is closest in this space. That centroid is then updated to include the new point. This gives rise to a given number of categories, into which the cycles are classified. The clustering is ‘learned’ in real time, without any prior knowledge of EGG waveshapes. The clusters are colour-coded for display in the VRP, with a separate VRP layer for each cluster. The number of categories, or clusters, must be chosen to be appropriate to the research question, usually 2...5 . Arriving at that choice usually requires some exploratory passes over the data. ‘Learned’ cluster data can then be saved, reloaded and used to classify new signals. To facilitate research work, most signals and results can be exported to files in common formats (.csv, .wav, .aiff), for further processing in other software.

2.2 Signal processing overview

The audio and EGG signals are processed in parallel, see Figure 2. From the microphone audio signal, four metrics are derived: the sound level SPL, the fundamental frequency f_o , the f_o periodicity (or ”clarity”), and the crest factor. The SPL and f_o serve to provide the plot position in the VRP. The clarity metric is used as a periodicity gate: ranging from 0 to 1, it must be close to 1.0 for the EGG processing to proceed. The default threshold is 0.96 . The crest factor gives a simple but useful indication of the high frequency content of the voice signal [4].

The EGG signal is first segmented into cycles. Then, each cycle is analyzed using a Discrete Fourier Transform (DFT) for its N lowest Fourier components, where N is typically 10 or less. From here on, the data rate is reduced, being proportional to the EGG cycle rate, rather than to the sampling rate.

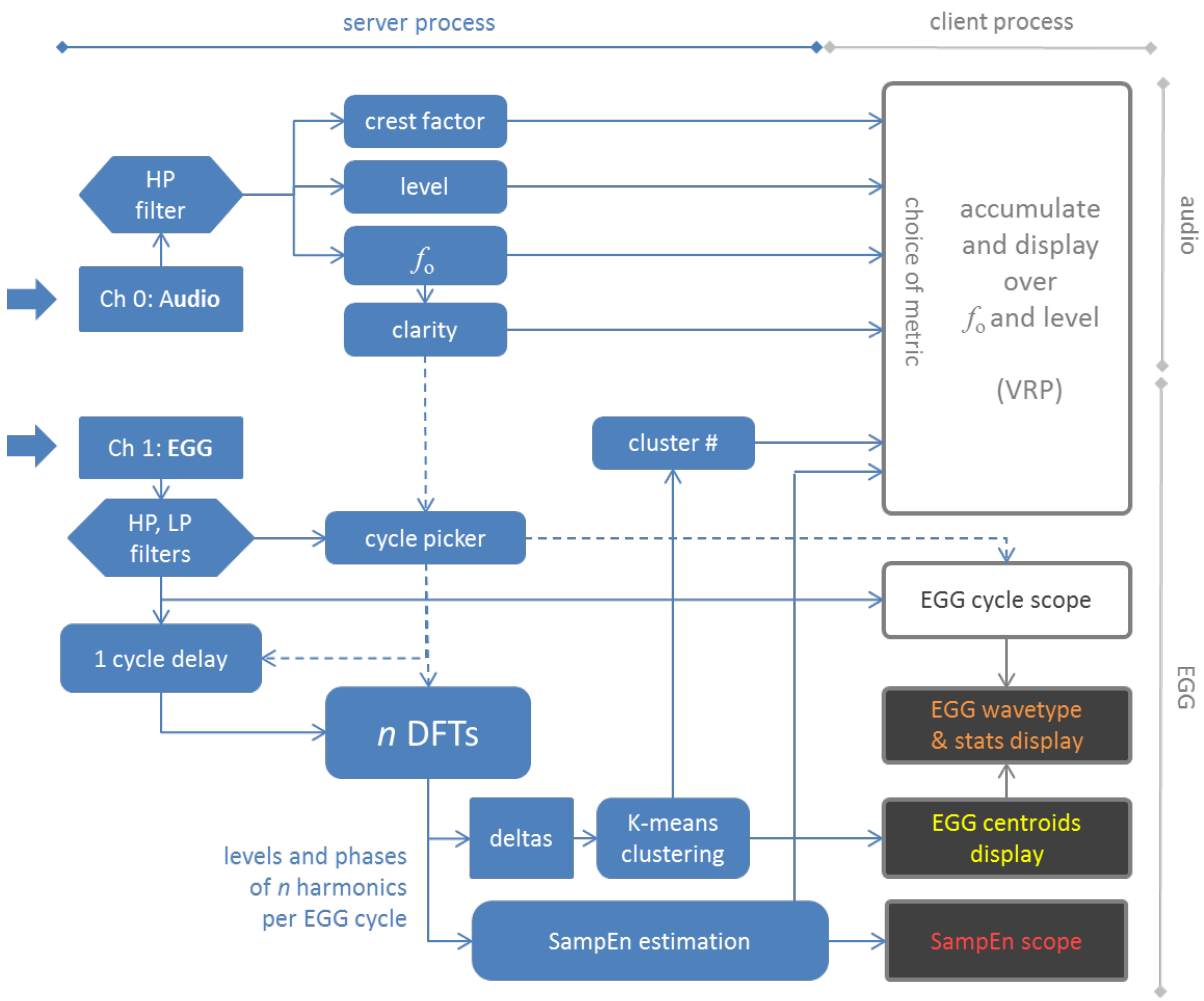


Figure 2. Overview of the signal processing in FonaDyn.

Each Fourier component is a complex number with a real and an imaginary part, or, equivalently, with a magnitude and a phase. The gain of EGG signals is difficult to calibrate, and also typically varies (due to varying larynx height, for instance). To minimize the influence of the variable gain of the EGG signal, *relative* magnitudes and phases are used instead. The first Fourier component, that is, the fundamental, is taken as the reference. For components 2...N, the *relative magnitude levels* and the *phase differences* to component 1 are taken as the input to a clustering algorithm. Additionally, for the residual EGG signal power that is *not* accounted for by the first N Fourier components, the system estimates the level of the total of that power, and uses it as an extra clustering dimension. The phase of the fundamental, too, is used as an additional clustering dimension. This is needed to enable a reconstruction of the approximated EGG waveform, from the cluster centroid values.

In parallel with the clustering, the time series of per-cycle DFT data are analyzed also for their ‘sample entropy’, or SampEn for short. This is a metric of phonatory stability that is designed to detect abrupt changes, such as register breaks, while suppressing minor instabilities.

2.3 Audio processing

2.3.1 Input selection

FonaDyn takes a microphone audio signal on the first A/D channel and an EGG signal on the second A/D channel; or, takes its input from two-channel audio files. Many input file formats are supported. The input signals can be recorded to a 2-channel WAV file. The FonaDyn sampling rate is 44100 Hz per channel. FonaDyn's own recordings of Voice+EGG are stored in 16-bit integer format.

When recording from the live inputs, the 'raw' microphone and EGG signals are written unchanged to the output file, with no prior processing. This is to avoid repeated preprocessing when analyzing a recording rather than the live inputs. It also enables the recordings to be used by other analysis systems, with no constraints having been imposed on the signals. When analyzing a first-generation FonaDyn recording, the input signals are identical to the live inputs of the A/D-converters (see also 3.2.6).

2.3.2 Audio preprocessing

A second order high-pass filter at 30 Hz is always applied to the microphone signal, to suppress low-frequency noise. This filter is not linear-phase, and does not need to be.

2.3.3 VRP metrics

From the microphone audio signal, four metrics are derived: the sound level SPL, the fundamental frequency f_o , the f_o periodicity (or "clarity"), and the crest factor.

- The *SPL* of the audio signal serves to provide the vertical plot position in the VRP. It is computed as follows.
  1. The conditioned audio input is squared.
  2. The squared signal is averaged over a 33 ms rectangular window. The reason for using a frame average (FIR) rather than an IIR low-pass filter is that the latter would incur sluggish onsets and drooping offsets.
  3. The 33 ms averages are median-filtered over 17 control rate periods (25 ms). This further reduces SPL lag at sudden signal onsets/offsets. The resulting total delay matches the parallel delays incurred in conditioning the EGG signal.
  4. The values are converted to dBFS (decibels relative to full scale).

- The f_o value serves to provide the horizontal plot position in the VRP. It is computed by a SuperCollider 'UGen' called `Tartini`, whose algorithm is based on autocorrelation via the FFT [5]. It updates the value of f_o at intervals of about 5 ms. In FonaDyn, f_o is measured in semitones, using MIDI note numbers with fractions. MIDI = 57.0 corresponds to f_o = 220.00 Hz.

- The *clarity* metric, also computed by the `Tartini` UGen, is used as a periodicity tester. Ranging from 0 to 1, it must be above a certain threshold for the EGG processing to proceed (the default threshold is 0.96). This is a fairly strict requirement, corresponding to stable phonation.

- The *crest factor* gives a simple but useful indication of the high frequency content of the voice signal [4]. It is computed as the ratio of the peak amplitude to the RMS amplitude, expressed in decibels. A sine wave has a crest factor of 3 dB, while a very bright voice signal can reach a crest factor of some some 15 dB.

2.4 EGG processing

2.4.1 Preprocessing

The absolute EGG peak amplitude is monitored during recording. If it comes within 0.5 % of full scale, a clipping warning is flashed on the screen. Clipping would immediately compromise the spectral analysis for the clustering.

The EGG signal is then

1. high-pass filtered at 100 Hz (-3 dB @ 80 Hz), using a 1024-point linear phase FIR filter. This suppresses the large near-DC content that is common in EGG signals;
2. median-filtered over 9 sample points; this reduces somewhat the 'crackle' that is common on some EGG devices, especially when the battery cells are aging;
3. low-pass filtered at 10 kHz, using a "brick wall" 64-point linear phase FIR filter (-80 dB @ 12 kHz).

This EGG preprocessing introduces a 34 ms delay, which is accounted for internally. It also limits the range in f_o : downwards, to 100 Hz, and upwards to 10 kHz divided by the number of DFT components in the analysis.

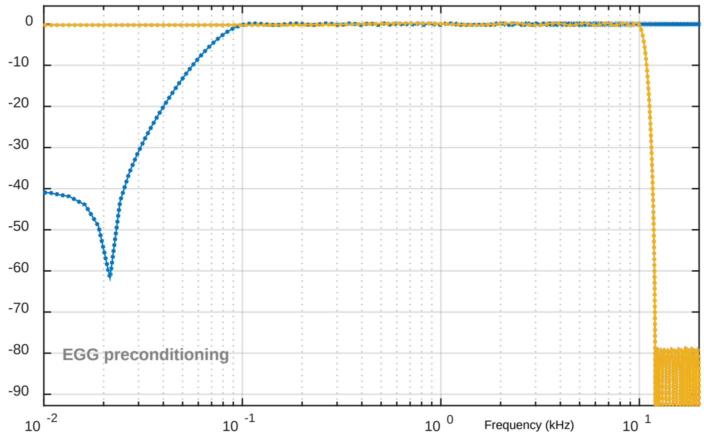


Figure 3.

Frequency responses of the EGG filters: high-pass (blue) and low-pass (yellow).

2.4.2 Period segmentation

FonaDyn implements two strategies for cycle separation: double-sided peak-following, after Dolanský [6]; and phase tracking. The double-sided **peak follower** is the simpler one; it is applied to the differentiated EGG signal (dEGG). The dEGG is computed as the differences between consecutive sample points. The positive peak-picker selects a point somewhere just prior to a local positive maximum of the dEGG signal. The ‘circuit’ then waits for a local negative maximum to occur, before allowing the next positive dEGG peak to trigger a new period. Using the dEGG rather than the EGG makes the triggering point somewhat less dependent on f_0 , but also more sensitive to noise.

Sudden changes in dEGG amplitude (which are common) may lead to one or a few lost cycles. Sudden increases in dEGG amplitude may cause the preceding cycle time to be estimated as slightly shorter.

The default method, however, is based on the **phase portrait**. The EGG signal is time-integrated and then paired with the original to form a complex-valued signal of the integrated EGG. By using this integrated signal rather than the more common Hilbert transform (which is somewhat similar to the *derivative* of the EGG), we obtain better rejection of low-level noise, and the cycle trigger point becomes similar to that in the alternative peak-following method described above. The phase of this pseudo-analytic signal is now computed as the arctangent of the complex pair; and then that *phase* signal is subjected to the Dolanský method described above. This cycle segmentation generally performs better with weak signals, as well as with fluctuating amplitudes, and it seems to give more distinct clusters overall. With unusual EGG signals, however, which may have multiple deep inflexion points per cycle, this method is sensitive to multiple loops in the phase portrait, and may be less reliable than the dEGG peak-following method.

Cycles longer than 20 ms (50 Hz) or shorter than 0.23 ms (4410 Hz) are rejected at this stage.

2.4.3 DFT analysis

A DFT analysis is performed of the lowest (and strongest) frequency components only of the EGG signal. For *N* components, the program computes *N* value pairs (magnitude and phase) cycle-synchronously over each EGG cycle. *N* can be chosen as 2...20; typically it will be 6...10. Because the DFT frame length adapts to the EGG cycle length, the DFT components are essentially equivalent to the harmonics of the EGG signal. A small quantization error arises here, in that the true EGG period time is not exactly an integer multiple of the sampling interval. In practice, though, such errors are absorbed by the subsequent statistical clustering.

The Fast Fourier Transform is *not* used, because the frame length here must be exactly one EGG cycle (to the nearest sampling interval), and because *N* is small. Instead, the desired DFT cosine and sine terms for the most recently completed EGG cycle are computed directly in the time domain. This also results in a constant CPU load for short and long cycles.

2.4.4 EGG waveform DFT components

For each EGG cycle that has been judged as valid, the first Fourier component (the "fundamental") is taken as a reference, for both magnitude and phase. The magnitudes, or absolute values, of the complex Fourier components $k \in [\ 2 \ldots N\ ]$ are computed, and their ratios to the magnitude of Fourier component 1 (the fundamental) are expressed as level differences ΔL_k . Using only the *relative* harmonic levels eliminates the effect of a variable gain on the EGG signal.

Similarly, the phases of the Fourier components $k \in [2 \ldots N]$ are computed relative to the phase of the fundamental, i.e., $\Delta\varphi_k = \varphi_k - \varphi_1$. The reason for computing the phases relative to φ_1 is that the cycle detection algorithms both find a cycle triggering point, whose location in the EGG cycle will depend somewhat on the current wave shape. By using the relative phases, this dependency is prevented from affecting the DFT results.

2.4.5 Residual energy

Since N is typically small, most of the high-frequency information in the EGG signal is lost. However, the overall spectrum slope of the EGG signal is typically quite uniform towards high harmonics, and thus the higher harmonics all tend to carry more or less the same information. Also, at low EGG signal levels, the higher harmonics often descend below the analog noise floor of the EGG hardware. In FonaDyn, the residual energy in all the harmonics $> N$ (plus any noise) is estimated by summing the energies in the N lowest harmonics, subtracting that from the total energy of the EGG signal, and again expressing the difference as a level relative to that of the fundamental. For convenience, this residual H is treated as though it were an extra harmonic, number N+1 . For low EGG signal amplitudes, H will tend to represent the relative level of the noise floor, rather than the relative level of the omitted harmonics.

This analysis method emphasizes the overall vibratory pattern of the vocal folds. It will tend to disregard very brief or transient events that are manifest mostly at high frequencies, such as multiple contacting events that occur very closely in time (small fractions of a cycle).

2.4.6 Phase of the fundamental

Since the phase of the residual energy H is undefined, that variable slot is used instead to retain and cluster the phase of the fundamental. This value is needed in order to reconstruct the EGG waveforms from the cluster centroid values. The phase of the fundamental is taken relative to the cycle trigger point found by the cycle detection. We do not want this phase to affect the clustering, though, so it is first down-weighted by 0.001.

2.4.7 Representation of phase differences

Since the phase angles φ_k are expressed in the range $]\ -\pi,\ \ \pi\ ]$, a phase whose value crosses $\pm\pi$ will cause a 2π jump. This must be avoided, since it could give rise to falsely disjunct data clusters. One could take the absolute phase difference, folded over π , thereby avoiding jumps. The clustering would then improve, but some information is lost, and it would not be possible to reconstruct the EGG waveform from the cluster centroid values. Therefore, each relative phase $\Delta\varphi_k = \varphi_k - \varphi_1$ is instead represented by the value pair $(\cos(\Delta\varphi_k), \sin(\Delta\varphi_k))$. This eliminates the discontinuities, at the cost of an extra clustering dimension per Fourier coefficient.

From here on, the EGG processing splits into two paths: DFT component clustering, and DFT component sample entropy estimation. The clustering is described first.

2.5 Clustering

2.5.1 Clustering dimensions

As described above, for each harmonic $k \in [\ 2\ ...\ N\ ]$, FonaDyn computes the relative level, and the cosine and sine of the relative phase. For each EGG cycle, this results in 3×(*N*-1) values. Using these values, plus the estimated level of the residual energy and the value pair $[\ \cos(\varphi_1), \sin(\varphi_1)\ ]$, the statistical clustering is performed in a space with 3×*N* dimensions. This is done using a real-time implementation of the algorithm 'online Hartigan *k*-means' [7]. Compared to other methods for clustering, the *k*-means method has these advantages: (1) it computes quickly even in many dimensions, and (2) the *number* of points already in the clusters does not affect the classification, only the centroid updates. The latter means that, in a data set with thousands of EGG cycles, a small minority of cycles of an unusual shape can still give rise to a cluster of their own, especially if they occur early in the recording. A typical example is the weak sinusoidal cycles at onset and offset of voicing.

For the clustering to be effective, all dimensions should have values extending over roughly the same numerical range. For this reason, the level difference values as fed to the clusterer are expressed in Bels rather than decibels. This makes for a better match to the (cos, sin) values, which are always in the range [-1...1].

Note that *none* of f_o, SPL and total EGG amplitude are input as parameters to the clustering algorithm. Also, the positions in the clustering space of the cluster centroids are *not* related to the locations of the coloured regions in the VRP plot. Rather, each centroid represents a particular EGG pulse shape. This means that affinity to a cluster is *not* given by proximity in the f_o/SPL-plane. However, different EGG pulse shapes do tend to occupy different regions in the VRP, typically with some overlap.

2.5.2 Resynthesis

In order to facilitate the user's interpretation of the clustering, the cluster centroid values of levels, cos and sin are used also to resynthesize and display the approximated cycle waveform, by addition of cosines (section 3.1.2). A potential problem here is that the cluster centroid values for sin and cos, since they are not strictly paired, no longer necessarily fulfil the trigonometric identity $\cos^2(\varphi) + \sin^2(\varphi)$

= 1 . In practice, though, tests with synthetic waveforms (triangle, sawtooth, square) have shown that such reconstruction works well enough.

2.6 Sample entropy

The 'sample entropy' of a signal [8][9] is an interesting metric that has found numerous biomedical applications. For brevity, it is often called SampEn. The SampEn is low for a regular, self-similar signal and high for a signal that is transient, erratic, or noisy. While others [10] with some success have taken the SampEn of high-rate, isochronous signals such as sampled EGG or audio, we have found that the SampEn metric is particularly effective for phonation data that are low-rate, cycle-synchronous. SampEn has a threshold or 'tolerance' parameter that keeps it at zero while phonation is stable, even with changing pitch, but when 'something unusual' happens, the SampEn peaks. This 'something' could be a voice break, such as those occurring between chest and falsetto voice [2], or other instabilities in phonation.

In FonaDyn, the spectral analysis produces a vector of values that is updated on every phonatory cycle. For each harmonic, we obtain a new value of the level and the phase. These sequences of numbers each provide the input to one of several SampEn estimators, running in parallel for all levels and phases of the first few harmonics. The final SampEn value is simply the sum of the SampEns for all levels and phases.

The algorithm used for estimating the SampEn is given in [11]. The number of harmonics is selectable; typically it will be smaller than for the clustering analysis. A local SampEn is computed over a short sliding window of w glottal cycles, where the integer w can be chosen by the user ('Window'). The window is advanced one cycle at a time, so a new value is obtained on every cycle. Another parameter is the sub-sequence length ('Length'). The 'Tolerance' setting is analogous to a noise threshold. See also section 3.5.5.

For computing the sample entropy of the phases, we have potentially the same wrap-around problem as described in section 2.4.7. Jumps of $\pm 2\pi$ would give large but meaningless peaks in the SampEn. Here, this is avoided by substituting the phase with its absolute value. This gives a continuous signal, for all phases; and the resulting ambiguity is of little consequence for the SampEn estimation.

2.7 Limitations

The analysis considers only the $N \leq 20$ lowest harmonics of the EGG signal, and typically 5 or 10 are used. This means that some high-frequency aspects, such as multiple contacting events in quick succession, might not be resolved.

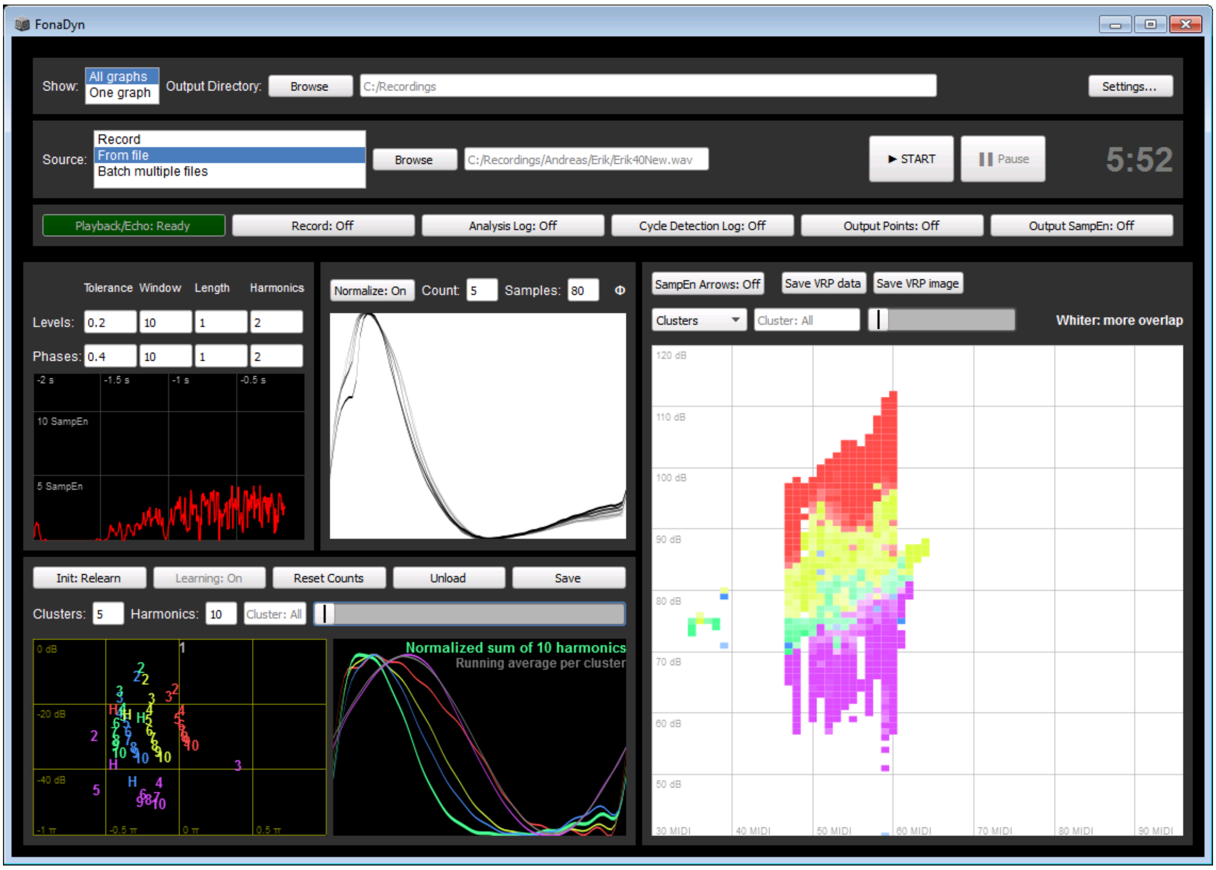
The preconditioning of the EGG signal means that the f_o should be 80 Hz or greater, and not higher than $10000/N$ Hz. The more these bounds are exceeded, the more the clustering will start to depend on f_o alone.

3 PART THREE - Using FonaDyn

3.1 Window layout

3.1.1 Main screen

The FonaDyn main screen is a bit like the control panel of a machine. It has no pull-down menus; almost all controls are visible (Figure 4).



<table>
<tr><td colspan="3">Panels 1-3, from top: General settings, Input selection and Start/Stop/Pause, Outputs selection</td></tr>
<tr><td>SampEn panel
SampEn during the last 2 s</td><td>Incoming EGG
waveform oscilloscope</td><td rowspan="2">‘VRP’ panel
f_o / SPL map</td></tr>
<tr><td>Cluster panel:
centroids</td><td>EGG pulse shapes,
or statistics</td></tr>
</table>

Figure 4. The main screen of FonaDyn.

The top row holds general settings. The second row selects the signal for input, controls START/STOP/PAUSE, and displays the accumulated time. The six buttons in the third row control the output options. The four subpanels with graphs show the analysis results, in real time, as described below.

You can use Tab or Shift+Tab to move the keyboard focus from one control to the next. *Numbers* can be edited with the keyboard, by dragging the mouse cursor vertically, or with the up-arrow and down-arrow keys. Ctrl and Shift increase the step size. There are no *text* fields that can be edited. All file names are entered using your system’s File Save/Open dialog boxes.

3.1.2 The Clusters panel

The Clusters panel has five buttons along its top:

Button	States	Action
Init	Relearn	On START, clear the current cluster data
	Pre-learned	On START, keep the currently loaded cluster data, for continued learning, or for classification
Learning	On	Continue learning, updating the centroids
	Off	Classify incoming data, without updating the centroids
Reset Counts	<push>	Set the cycle counts of all clusters to zero, now. All centroids are initialized to the current DFT values, but they soon diverge. Useful for initializing and for clearing spurious undesired centroids. Avoid repeated pushes in rapid sequence; this may destabilize the program.
Load	Load	Load a cluster data file, for initialization or classification
	Unload	Clear all cluster data
Save	<push>	Save the cluster data to a file (`*_clusters.csv`)

If the filename you enter for **Save** does not end in `.csv`, FonaDyn will append `_clusters.csv` to the name. If the filename you enter *does* end in `.csv`, then FonaDyn will not change it.

A *cluster centroid* is a set of values that describe the average location of all the cycle points in the clustering space. In the centroids display, each *colour* corresponds to one centroid (and, equivalently, to one cluster). In Figure 5, one centroid (green) is shown. Here, we have specified 6 harmonics, so one centroid has 3×6 dimensions: 6 relative levels, and 6 sines plus 6 cosines for relative phases. The thin gray line shows a running average of the most recent EGG pulses that were assigned to this cluster.

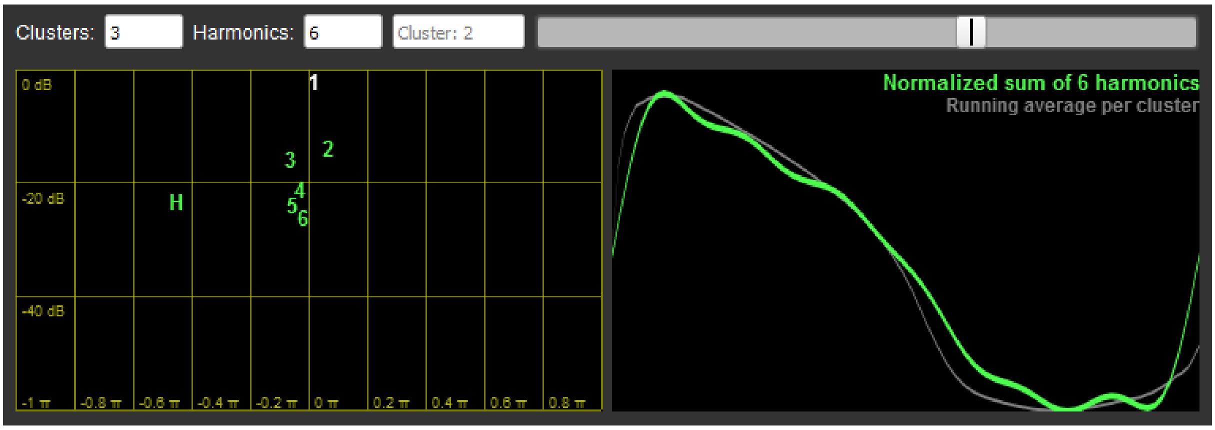


Figure 5. The graphs in the Clusters panel.

The grid to the left shows the levels and phases of the EGG harmonics, relative to the fundamental. By definition, then, the fundamental or first harmonic has the level 0 dB and the phase 0 radians. The white '1' at top center (0 dB, zero phase) is thus implicit and shown for visual reference only. The data points are at the top-left corner of the glyphs. Here, the second harmonic '2' has a relative level of about -12 dB and a relative phase of about +0.05π radians. Finally, the 'H' shows the relative level of the residual power of all Higher harmonics, and also the pHase of the fundamental, relative to the cycle trigger point. So, the number 6 here actually stems from harmonics 2...6 plus the residual. If you were to string out the digits in sequence from left to right, keeping their heights, you would get the typical power spectrum of the EGG pulses in the given cluster.

The graph to the right has three different display modes, as shown in Figure 6. By clicking on this graph, you can toggle between a bar graph, a single clustered waveform or all clustered waveforms. The horizontal scroll bar, too, selects one or all clusters.

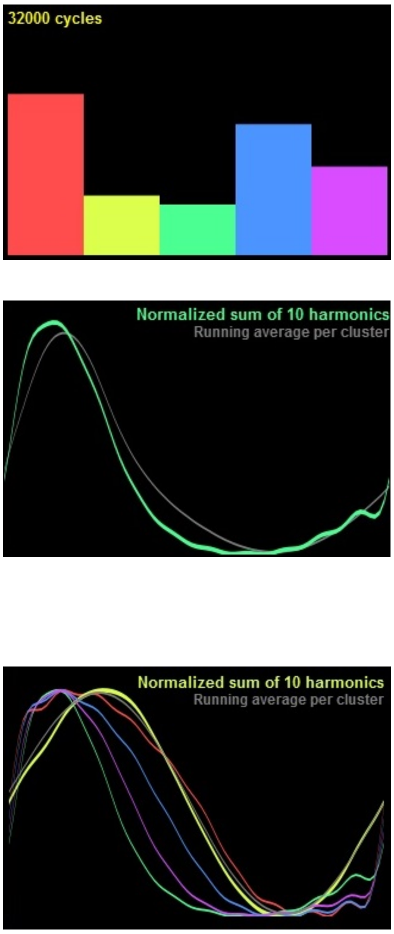


Figure 6. Cluster statistics display options.

a) *Bar graph mode, with EGG cycle counts, per cluster. The number denotes the scale of the vertical axis, which rescales automatically. Click on one of the bars to display (b). Click near the top of the graph to display (c).*

b) *EGG wave resynthesis display, with one cluster selected. Both time and amplitude are cycle-normalized. Vocal fold contact area increases upwards. Gray line: a running average of recent pulses in the selected cluster. Green line: EGG pulse resynthesized from one of the cluster centroids. Click on the graph to display (a).*

c) *EGG wave resynthesis display, with all clusters selected. Both time and amplitude are cycle-normalized. Here, for example, the yellow signal (no vocal fold contact) is actually much weaker than the others. Click on the graph to display (a).*

The rippling which can be seen in the resynthesized (colour) curves is an artefact of truncating the spectrum after a few harmonics. It is known as Gibb's phenomenon, and it is not a property of the EGG signal.

3.1.3 The VRP panel

The VRP panel can be switched to show one of several acoustic metrics, or the prevalence of each or all clusters (Figure 7). The horizontal axis is the f_o in semitones (57 MIDI = 220 Hz); or, right-click to display the f_o axis in Hz. The vertical axis is the sound level in dB. This should be calibrated to correspond to SPL @ 0.3 m microphone distance, see section 3.2.4. Metrics (a), (b) and (c) are derived from the audio signal, the rest from the EGG signal.

For the example in Figure 7, an amateur male singer repeated soft-loud-soft /ɑ/ vowels on several constant pitches over more than an octave. This recording took about 6 minutes. (a) ‘Density’, where darkest gray means >100 EGG cycles. Optional black triangles indicate a SampEn above threshold. (b) ‘Clarity’ showing accepted cycles (green) and rejected cycles (gray). (c) Mean level of the crest factor (peak-to-RMS ratio) of the audio signal, where red means >12 dB. (d) Maximum SampEn; more brown means less stable phonation. (e) Dominant EGG waveshape cluster by colour. The ‘dominant’ cluster is the one with the most cycles in a given cell. Less saturation signifies more overlap. (f) - (j) Actual extents of individual cluster wave-shapes. (f) ‘red’ cluster waveshapes, strongest phonation; (g) ‘purple’ cluster waveshapes; here, firm phonation with full vocal fold contact; (h), (i) ‘yellow’ and ‘blue’ cluster waveshapes; here, fairly soft phonation with brief contact; (j) ‘green’ cluster: softest phonation with no vocal fold contact, i.e., a nearly sinusoidal EGG.

Interestingly, we see that the vocal folds can vibrate without contacting at SPL’s as high as 70-80 dB.

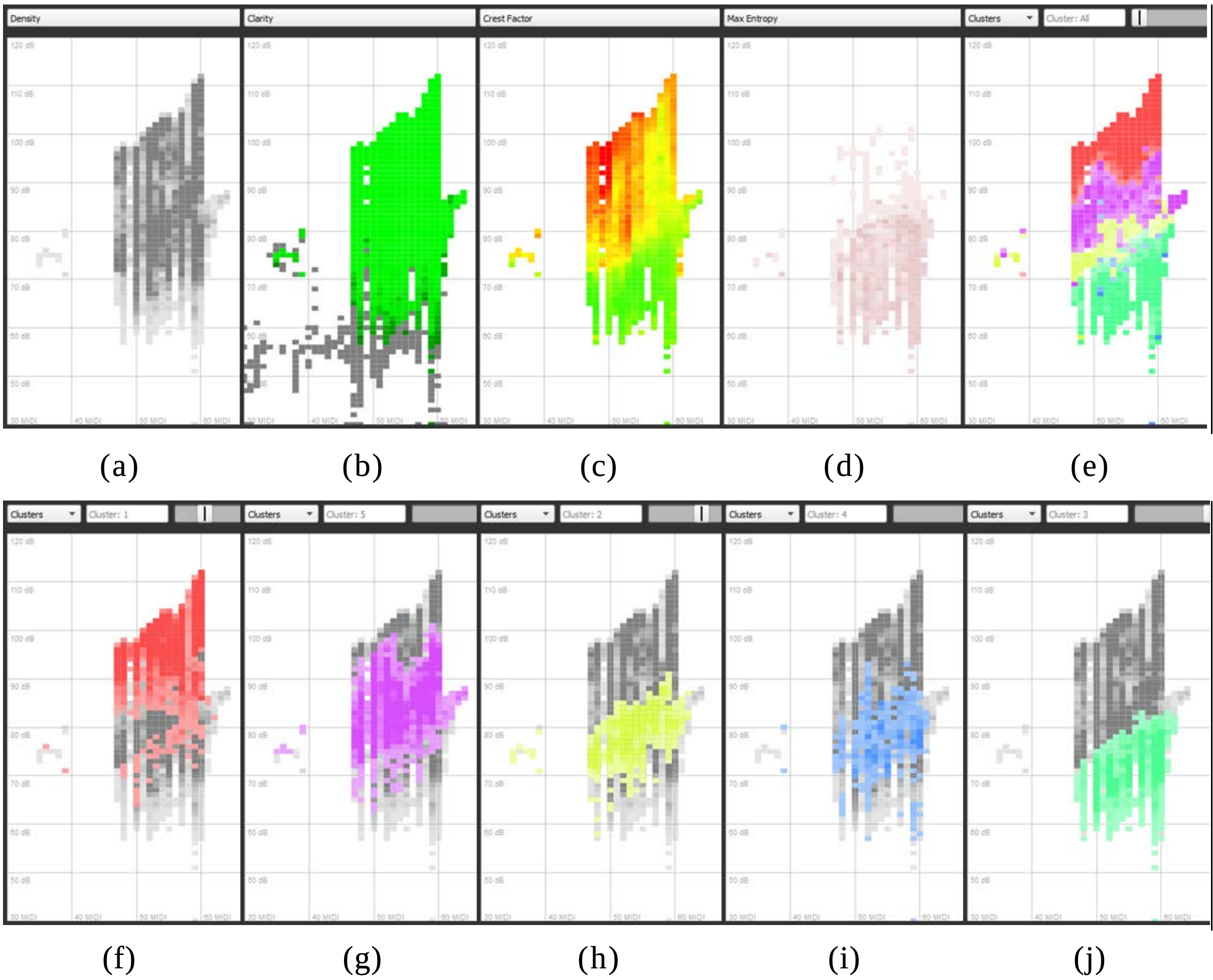


Figure 7. Displaying different metrics in the VRP panel.

All the data shown in Figure 7 can be saved to a .CSV text file for further analysis in other software. Press **Save VRP data** to open a standard File Save dialog box. If the filename you enter there does not end in `.csv`, then FonaDyn will append `_VRP.csv` to the name. If the filename you enter *does* end in `.csv`, then FonaDyn will not change it.

When you press **Save VRP image**, a partial screen dump is generated and shown in a preview window of its own. When you close this window, a Save File dialog appears. Also, a list of available image file formats is printed in the Post window of the SCIDE. Choose one, and *type it in as the extension* to the image filename that you specify. Or, you can leave the preview window open, for easy visual comparison with your *next* VRP plot.

3.1.4 The Sample Entropy panel

The SampEn metric is computed from the cycle-time series of the EGG harmonic magnitudes and phases, by default, from two of each. The value shown by the scrolling red curve is the sum of those four SampEn values. The default values for Tolerance, Window length and sequence Length (the last two in EGG cycles) have been found by trial and error to work fairly well, but they may need to be adjusted in different scenarios (see also section 3.5.5).

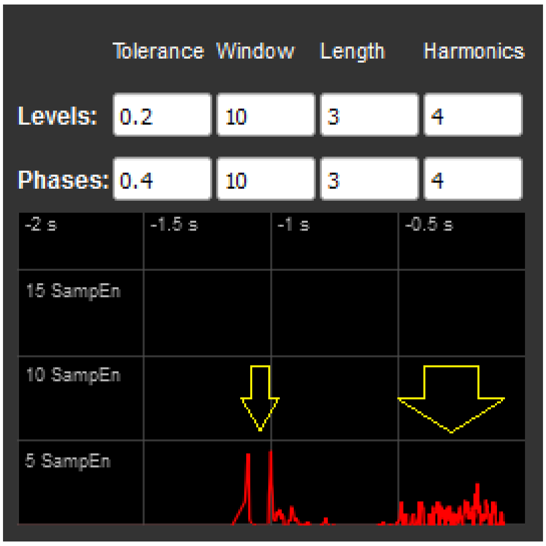


Figure 8. The SampEn Panel. This shows a short excerpt from an upward glissando by a male subject. Arrows (added here) indicate voice breaks, and an episode of unstable EGG waveform.

Increasing the Tolerance suppresses the influence of small variations. Increasing the Window makes a smoother curve and reduces the temporal resolution. Increasing the Length can make the SampEn peaks more localized.

The display scrolls, showing the most recent two seconds. You can save the entire time history of the SampEn metric, by creating a general Log file (many channels), or a SampEn Log file (one channel, cycle by cycle).

3.1.5 The 'Moving EGG' panel

This panel displays the incoming EGG cycles in real time. The period length is normalized to the width of the display frame. By default, the peak-to-peak amplitude is normalized to the height of the display frame. To see the actual EGG amplitude, relative to full scale, choose **Normalize: Off**. This is useful for checking the amplitude of the input signal.

The display draws the n most recent cycles with a fading gray scale. Change n by entering a different value for **Count**. The cycle curves are rendered as k piecewise linear segments; change k by entering a different value for **Samples**. Increasing Count or Samples may give a nicer image, but also increases the processing load.

The rightmost symbol at the top indicates the type of cycle segmentation (section 2.4.2), with Φ for the phase tracker, and Λ for the peak follower. You can change this option in the **Settings...** dialog box.

3.1.6 SampEn arrows and shading

The **SampEn Arrows** button on the VRP panel activates a special display mode. When the SampEn metric exceeds a given threshold, a small black arrow is plotted showing in the current VRP cell, showing also the direction in which f_0 and SPL were moving when the waveshape perturbation occurred. The idea is to see where voice breaks tend to occur, and if their position depends on where the voice is going. So far, though, this issue has not been pursued with FonaDyn. In soft phonation, one tends to get a profusion of arrows that is not very informative. The VRP can also display a brown shading representing the *maximum* SampEn seen in each cell.

3.1.7 The Settings… box

To reduce screen clutter, some diverse settings that are infrequently used have been placed in a separate dialog box.

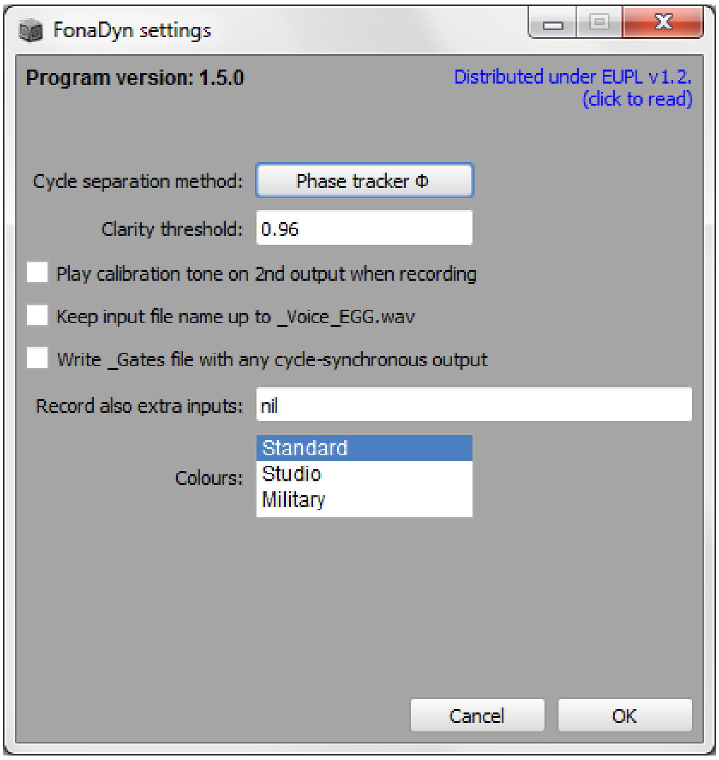


Figure 9.

The Settings... box.

Click the blue text to open the license text from the Internet.

Cycle separation method selects Phase tracker or Peak follower – see section 2.4.2 .

Clarity threshold allows you to adjust the threshold for cycle regularity. This refers to the regularity of the *audio* signal, not the EGG.

Play calibration tone – see section 3.2.4.

Keep input file name – see section 3.4.

Write _Gates file – see section 3.4.

Record also extra inputs – see section 3.2.7.

Colours selects one of the available colour schemes. Since a black background often works poorly in print, you may prefer the lighter 'Studio' colour scheme for screen-dump illustrations that will be printed.

In the current version, there is no way of saving these Settings for the next session. If the default values are not the ones you want, you must change the settings explictly, whenever FonaDyn has been restarted.

3.2 Recording

3.2.1 Recording environment

Use a quiet room. The fact that FonaDyn uses the 'clarity' metric as a criterion for acceptance means that the EGG analysis gate will be opened whenever the *audio* signal from the microphone is *sufficiently periodic*, even if it is very soft. The rationale for this design is that the signal-to-noise ratio of the audio channel is typically much better than that of an EGG device; and while a weak EGG signal is often electrically rather noisy, its lower harmonics can still be analyzed. It follows that any tonal sound in the recording room will open the EGG analysis gate, even something other than the subject's voice, including other voices, a piano, or machinery such as fans or buzzing light fixtures, etc.

The recording environment should follow the established recommendations [12] for VRP acquisition, with regard to ambient noise and room absorption. If the computer or any other source of tonal or soft fan noise must be present in the recording room, then the microphone should be of a cardioid type and be pointed exactly away from the noise source. If the subject needs prompting pitches, auditory stimuli, or a background audio track, these should be presented over closed circumaural headphones.

Headphones can also be useful for restoring some hearing-of-self in anechoic or very dampened recording rooms. Some audio interfaces even have a built-in reverb effects unit, which can help, if applied in moderation. Just be sure that the reverb is not routed into the signal that is being recorded.

3.2.2 Normal setup

By default, the two output channels of your audio interface play a copy of what the microphone is picking up. In this way, you can monitor the incoming audio signal on headphones, and check that it is free of noise and hum. You may wish to connect a loudspeaker instead, for listening to existing recordings together with other people.

The button **Playback/Echo** turns the audio output On or Off. If you have a loudspeaker connected, in the same room as the subject, it can be useful to choose Off prior to recording, to prevent feedback. This must be done before pressing ▶START. Or, monitor with headphones.

By default, processing and display are started when you press ▶START, but nothing is saved to file. This is useful for checking levels, and for working interactively with real-time feedback.

3.2.3 Checking the EGG level

Connect the EGG device and strap on the electrodes for acquisition. Turn on the EGG device and ask the subject to phonate. In the oscilloscope panel, choose **Normalize: Off**. Press ▶START, and wait for that button to display ■STOP. Adjust the output level of the EGG device such that you get a clearly visible signal. Ideally, it should exercise the major part of the vertical axis, for the strongest signals.

FonaDyn monitors the EGG signal amplitude during recording. If the usable range is exceeded, the word **CLIPPING!** is flashed for about a second. If this happens, reduce the output level of your EGG device. If necessary, insert a signal attenuator between the EGG device and the input to your audio device.

When the EGG amplitude appears to be satisfactory, press ■STOP, and wait until that button again displays ▶START. Restore **Normalize:** to **On**.

3.2.4 SPL calibration

In order for the SPL axis in the VRP to be correct, the gain of the microphone amplifier has to be calibrated prior to recording. The procedure is different depending on if you are using a head-mounted boom microphone at close range (A), or a stand-mounted microphone at 30 cm in front of the subject's mouth (B). To do this, you will need a hand-held sound level meter, and, for (B), an active loudspeaker (i.e., with a built-in amplifier).

Turn on the sound level meter, and select a flat frequency response or the C-weighting charactistic. Do not use the A-weighting characteristic. If available, select "slow" response rather than "fast".

3.2.4.1 (A) Head-mounted boom microphone

Because head-mounted microphones are very close to the mouth, their pick-up is also very sensitive to distance. You will need to use the subject's own voice as a sound source, and you will need to make a new calibration every time the boom microphone is hung anew on the subject.

- Have the subject wear the microphone boom and adjust the capsule so that it is about 7 cm from the center of the mouth.

- Place the sound level meter so that its tip is 30 cm in front of the subject's mouth, and orient the meter so that both the subject and you can read it while you are sitting at the computer.
- Select **Source: Record**.
- Select **Playback/Echo: Ready**.
- Press ▸ **START**.
- Ask the subject to sustain a vowel at a steady level around 80 dB.
- On your audio interface, or in its control panel app, adjust the input gain for the mic signal such that the moving cursor on FonaDyn's VRP display sits at the same SPL as the value displayed on the level meter (to within the nearest decibel). The microphone gain is now calibrated. If you are recording the calibration, also read the level value out aloud into the microphone. Then press ■ STOP.
- Make a note of the calibrated gain setting. Also, the software for your audio interface might have an option for saving its settings.

3.2.4.2 (B) Stand-mounted microphone

For convenience, FonaDyn provides a built-in calibration tone which gives better accuracy in the calibration. If you want to use it, route the *second* output channel of your audio interface to a loudspeaker. Place that loudspeaker about one meter from the microphone that will be recording the subject. The exact distance is not critical. If you prefer, you can use any other constant tone generator, set to 200-300 Hz.

- Place the microphone on its stand, at 30 cm in front of the subject's mouth. A fixed head rest can be useful to help the subject stay at that distance. An error in distance of 10% incurs about 1 dB of error in the level reading.
- Click the button **Settings...** . In the box that appears, check the option "**Play calibration tone on 2nd output when recording**", and choose OK.
- Select **Source: Record**.
- Select **Playback/Echo: Ready**.
- Press ▸ **START**. FonaDyn will now output a 250 Hz tone to the loudspeaker. Hold the tip of the sound level meter close to the microphone (within two centimeters or less). Adjust the volume of the loudspeaker so that the level meter shows about 80 dB. The actual value is not important.
- On your audio interface, or on its control panel, adjust the input gain for the mic signal such that the moving cursor on FonaDyn's VRP display sits at the same SPL as the value displayed on the level meter (to within the nearest decibel). The microphone gain is now calibrated. If you are recording the calibration, also read the level value out aloud into the microphone. Then press ■ STOP.
- Make a note of the calibrated gain setting. Also, the software for your audio interface might have an option for saving its settings.
- In the **Settings...** box, turn off the calibration tone.

3.2.5 Recording live signals

- In the top panel of FonaDyn, check that the **Output Directory** is the one where you want new recordings to be stored. If it is not, use the adjacent **Browse** button to select another directory.
- In the **Source** list, select **Record**.
- Select **Record: Ready**. An empty text field appears, where the name of the new file will be shown. You cannot choose the file name yourself, even though this field is editable. FonaDyn creates a file name based on the current date and time (see also section 3.2.8). The timestamp makes the filename unique.
- Press ▶ START. After a moment, the Record button becomes bright red and indicates that **Recording** is in progress.
- Have the subject perform the phonatory production procedure.
- Press ■ STOP. After a moment (possibly quite a few seconds), the Record button returns to the dull red **Ready** state**.**
- You may want to copy the resulting file name of the `_Voice_EGG.wav` file and paste it into your log of the experiment, with a comment on what was recorded. You can of course also rename the file afterwards, if you wish.
- When done, select **Record: Off**. It is easy to forget it in the **Ready** state, in which case new files will consume your disk space whenever you press ▶ START.

3.2.6 Re-recording during analysis

Even when you select a file for analysis rather than the live inputs, it is possible to re-record the input file. This would seem rather pointless, but for two things. First, the re-recorded file will receive a new time-stamped file name, with the same time stamp as any other output files that you may be generating in the same run. This may make it easier to track different analyses of the same file. Second, the re-recorded file contains not the raw input EGG and voice signals, but rather the preconditioned signals, which allows you to inspect the signals as they are after conditioning, if you wish. The EGG signal will be about 34 ms delayed relative to the audio track. To remind you that you are re-recording, the Record button turns **orange** rather than **red**.

3.2.7 Recording additional signals in parallel

FonaDyn itself normally records a stereo WAV file only, with voice and EGG. If you want to record additional *audio-rate* signals in synchrony with voice and EGG, a way of doing that is to record using instead some digital audio workstation (DAW) software such as Reaper, ProTools, Logic or other multitracking programs. You can then export the voice+EGG signals to a stereo WAV file that FonaDyn can analyze, and export the other tracks to synchronized files in the format of your choice.

Sometimes, though, one may wish to record also *slow physiological signals* such as subglottal pressure, larynx height, or breathing-related signals. These cannot be recorded by audio interfaces, because the latter block DC, and AC signals below about 20 Hz. However, some audio interfaces offer so-called ADAT optical connections, each of which adds another 8 inputs or outputs. Enthusiasts in the music community for analog synthesizers have developed DC-coupled ADAT-linked converters for slow control voltages [13]. FonaDyn can acquire such signals, downsampling them to a fixed frame rate of 100 Hz. No anti-aliasing is performed on these signals, so they should be band-limited to <50 Hz.

Be aware that such ‘consumer’ devices are not generally certified for safe use with body-contact transducers. Although malfunction is rare, a precaution would be to power them from batteries rather than from the mains.

To activate this feature, first activate the necessary number of hardware inputs in the SuperCollider startup file, and restart SCLANG. In FonaDyn, open the **Settings** dialog. In the text field **Record also extra inputs**, type a list of the inputs to which you have connected slow signals. The list must consist of comma-separated integers, and must be enclosed in square brackets, like so: **[10,11,12,13,14]** . The inputs must refer to active hardware inputs, where the first two (usually **[0, 1]**) are reserved for the microphone and the EGG. The inputs do not have to be contiguous nor in any particular order. The order that you specify is the order in which the signal tracks will appear in the output file.

The output file will be a multichannel WAV file of 16-bit integer data, with as many interleaved channels as you have specified in the list. The signals will be synchronized with those in the Audio+EGG file. The filename will have the same timestamp as the Audio+EGG file, followed by “_Extra.wav”. That file will report its sampling rate as being 44100 Hz, but this is not correct; its actual sampling rate per channel is 100 Hz.

To turn off the recording of these extra channels, clear the text field **Record also extra inputs**.

3.2.8 Notes on using FonaDyn with RME audio interfaces

The digital audio interfaces from RME are very versatile and ideal for multichannel acquisition. The models Fireface 400, UC and UCX, as well as the Babyface all have their microphone preamps on inputs 1 and 2. This is what FonaDyn expects. The larger models Fireface 800, 802, UFX and UFX+, however, all have their microphone preamps on inputs 9-12. This requires a little extra configuration, which can be done in RME’s TotalMix software. It is described in the separate document *Using FonaDyn with RME audio interfaces*.

3.2.9 Using FonaDyn without an EGG device

If you are interested only in the VRP as such, and do not have an EGG device at hand, you still need to feed an “EGG-like” signal to the second input. One way is just to branch a line-level copy of the microphone signal to the second input, preferably with a lot of low-pass filtering. The cluster displays will probably make little sense, and the VRP display may seem a little jerky. The displays of Density, Clarity and Crest factor will be correct, though. Or, if you are curious, you can test what FonaDyn does with an accelerometer signal or a photoglottographic signal, instead of the EGG. We haven’t yet had time to do that.

3.3 File locations

The **Browse** buttons open a file system dialog for opening or saving files. If the default location is not convenient for you (it probably isn't), you will need to navigate to the right place every time. Unfortunately, SC gives the programmer no way to specify a default location. However, the Open File dialog usually has at the top a drop-down list of recent locations, which helps a little.

An exception is that you *can* specify a persistent default directory for recordings, which is useful, because the standard location is rarely the one you want. To do so, add the following line in the SC startup file, with your desired location in double quotes:

```
thisProcess.platform.recordingsDir_("C:/Recordings");
```

In SC code such as this, always use *forward* slashes (/) in pathnames, even on Windows. Once you have restarted SuperCollider, FonaDyn will display this path in the field **Output Directory**, and recordings as well as other log files will be saved in that directory.

3.4 File names and file formats

FonaDyn can export and import several types of data file that can be used for mathematical processing and display with Matlab and other software. Some Matlab examples are provided in the 'FonaDyn Extras' folder. The signal file formats are documented also in the online documentation for the class **VRPViewMainMenuOutput**.

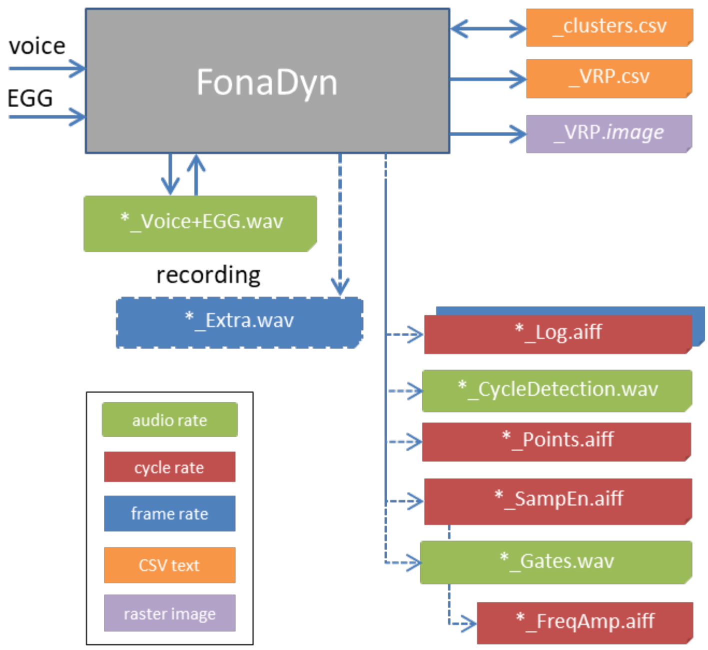


Figure 10. Summary of file types handled by FonaDyn.

When running, FonaDyn processes either live inputs or an existing recording. By default, the output files that contain *signals* are automatically given a file name beginning with a time stamp YYMMDD_HHMMSS_ (shown as * below). The time is that of the start of *recording*; or, if analyzing a file, from the starting time of the *analysis* (not the time-stamp of the analyzed recording – that would risk confusion if the same file were analyzed repeatedly with different settings). All signal output file types are optional, and all can be written to simultaneously. To the time stamp is appended a string suffix indicating the type of the output file.

If instead you prefer the output files to receive the same name as the input file, go to the **Settings…** box and check that option. The output files will then inherit the original time stamp (or other name), which makes it easier to see which files are derived from which input signals. This will work only for input files whose names end in “`_Voice_EGG.wav`”.

Recordings are made into 2-channel files at 44.1 kHz per channel and 16 bits resolution, named `*_Voice_EGG.wav` .

Analysis Log. This is a multichannel file called `*_Log.aiff` . It contains tracks for the time (s), the f_0 (semitones), sound level (dB), clarity (0...1), crest factor (dB), SampEn, cluster number, and the levels (Bels) and phases (radians) of all analyzed harmonics of the EGG signal. The levels and phases here are absolute, i.e., relative not to the fundamental but to the cycle trigger. The frame rate (or “sampling rate”) in this file is selectable as cycle-synchronous, with new data for every EGG cycle, or one of 50, 100 or 200 Hz. Frames of accepted cycles only (above the clarity threshold) are written to this file. That is why the time track is helpful; without it, the absolute times of each cycle would be harder to reconstruct (see below). The data is stored as 32-bit float values. These are *not* scaled down to ±1.0, as is the convention for normal audio files, and hence the signals in most of the tracks will appear to be out-of-range, if such a file is opened in an audio editor.

Cycle Detection Log. This is a two-channel, 16-bit file called `*_CycleDetection.wav`, containing the conditioned EGG signal, and the corresponding cycle trigger pulses. This file enables post-inspection of whether or not the cycle triggering was accurate.

Output Points. This file type (`*_Points.aiff`) contains as many tracks as there are harmonics. It contains the cycle-synchronous level and phase *differences*, for accepted cycles only. This is almost the data that is input to the clustering algorithm; see section 2.5 for details. Not scaled. The last delta-level track contains the relative level of the residual high frequency energy. The last delta-phase track contains *twice* the absolute phase of the fundamental (for internal use).

Sample Entropy. This is a single-channel, cycle-synchronous file `*_SampEn.aiff`. Not scaled.

Frequency and Amplitude. This file type does not have any on/off button, but such a file is always written when either the SampEn measurement is written, or the Points are written. The reason is that you often want to see these metrics together. The file is a cycle-synchronous AIFF file with floats as samples. These files are called `*_FreqAmp.aiff`.

Gates Log. This file is called `*_Gates.wav`. It contains five tracks of audio-rate 16-bit samples, with the raw EGG, the conditioned EGG, and three trigger tracks. It shows exactly where all EGG pulses were segmented and also which of the pulses that were regular enough to be retained for further analysis. This enables close scrutiny of the data input to the DFT analysis, as well as the reconstruction (e.g., in Matlab) of cycle-by-cycle data with absolute times. Because it becomes big, this file is written only if you have checked that option in the **Settings…** box, and only if there is some other simultaneous cycle-rate output being written.

Physiological signals can be saved synchronously into multichannel WAV files at 100 Hz per channel and 16 bits resolution, named `*_Extra.wav` . See section 3.2.7.

Cluster data and VRP data are saved as **text files**. Their file names are *not* given an automatic time stamp; rather, you must choose a full name yourself. You will probably want to encode the relevant settings into the file name in your own way. The same applies for image files.

Cluster data. When an analysis is completed, the centroids of the resulting clusters can be saved and then reloaded. Typically, you would do this to continue learning with more input files, or to classify other signals using the same cluster data, or to use the cluster data in analyses outside of FonaDyn. Figure 11 shows an example of a `*_clusters.csv` file opened in a spreadsheet, with added comments. Matlab examples are provided that show how to resynthesize EGG cycle shapes from this data.

	A	B	C	D	E	F	G	H	I	J	K	L	M
1	4277	-1.1125	-1.887	-2.354	-3.8626	0.4308	0.1371	0.1646	0.0003	-0.7807	-0.6472	-0.4933	-0.0009
2	8305	-0.6012	-1.3393	-1.8837	-2.3313	0.6181	0.1997	0.2316	0.0006	-0.7734	-0.9389	-0.858	-0.0008
3	8931	-2.905	-3.8167	-4.3397	-3.625	-0.2025	0.1015	0.1032	5E-05	-0.3321	0.3709	-0.007	-0.001
4	19605	-1.0258	-1.5655	-1.9074	-1.9629	0.7232	0.8096	0.7966	0.0003	-0.6728	-0.5271	-0.5659	-0.0009
5	22124	-1.2888	-1.5077	-1.8943	-1.8424	0.9706	0.9553	0.9772	2E-05	-0.0479	-0.2532	0.0565	-0.001
6													
7	*Column*	*Contents*											
8	A1:A5	Cycle counts in clusters 1..5											
9		*Centroids of*											
10	B:D	relative levels of harmonics 2..4 (in Bels)											
11	E	relative level of higher harmonics (in Bels)											
12	F:H	cosines of relative phases of harmonics 2..4											
13	I	cosine of the phase of the fundamental * 0.001											
14	J:L	sines of the relative phases of harmonics 2..4											
15	M	sine of the phase of the fundamental * 0.001											

*Figure 11. Example of cluster data file, opened in a spreadsheet. This example is for 5 clusters and 4 harmonics. The rows 7-15 and the colouring are explanatory only – they do not appear in the *_clusters.csv file.*

VRP data. When an analysis is completed, the data underlying the VRP graph can be saved to a CSV file (press **Save VRP data**). An example of a `*_VRP.csv` file is shown in Figure 12. Each line corresponds to an occupied cell in the diagram. Matlab examples are provided that show how to plot VRP-like charts from this data.

	A	B	C	D	E	F	G	H	I	J	K	L
1	MIDI	dB	Total	Clarity	Crest	Entropy	maxClust	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
281	59	90	35	0.99925	2.20147	0	1	35	0	0	0	0
282	61	90	81	0.9995	2.83695	0	1	64	0	0	0	17
283	63	90	64	0.99907	3.33263	0	1	52	12	0	0	0
284	45	91	59	0.998	4.12796	0	4	0	17	0	42	0
285	46	91	2	0.99559	3.68363	0	2	0	2	0	0	0
286	47	91	84	0.99916	3.8425	0	4	0	40	0	44	0

Figure 12. An example of a VRP data .csv file, opened in a spreadsheet. Columns A and B give the cell coordinates, column C the total number of cycles in the cell, D the most recent value of the clarity metric, E the average level of the crest factor, F the maximum value seen of the SampEn metric, G the number of the cluster with the largest number of cycles, H...L the cycle counts per cluster.

The cycle counts in this file are absolute, that is, they are not weighted by f_o . This means that 1 second of phonation results in 100 cycles at 100 Hz, but 400 cycles at 400 Hz. You can obtain the approximate phonated time by dividing the cycle counts by the corresponding f_o , where

$$f_o = 220 \cdot 2^{\left(\frac{MIDI-57}{12}\right)}$$

In this VRP file, f_o is quantized to whole semitones (6% increments), so the maximum error in the duration for one cell would be ±3% . (In the *.aiff log files, MIDI(f_o) is given with a decimal fraction to a high resolution.)

For the **column separator** in CSV files, FonaDyn uses the semicolon (;). If this is inconvenient, you can change it in the source code file `VRPMain.sc`. It is currently not possible to change the **decimal character** in FonaDyn to anything other than the period (.) .

The Region settings in the Windows Control Panel allow you to choose the decimal character, which is then applied system-wide by all apps that heed this setting (FonaDyn does not). In addition, Microsoft Excel allows you to specify its own decimal character, independently of the Control Panel setting. Not exactly simple, but workable.

3.5 Analysis

This section applies to the analysis of both 'live' and prerecorded signals.

3.5.1 Clustering parameters

Ideally, choosing the *number of clusters* should be as easy as choosing the number of phonation types that you want FonaDyn to identify. To discriminate between modal and falsetto singing, for example, two clusters could suffice, in principle. But there is no way of knowing beforehand if the EGG waveform really does change in a way that is so cleanly separable. For example, you may find that you get better discrimination with three clusters, of which two are needed to catch all the falsetto-mode cycles [3].

Therefore, a good strategy may be first to specify more clusters than you actually need, and let FonaDyn try. The most common wave-shapes will tend to produce a few well-populated clusters, while the other clusters will contain much fewer cycles. For research work, it helps to edit your recordings so as to eliminate pauses. If your signal contains pauses or other non-voice events, these may give rise to a 'trash' cluster or two, holding weird pulse shapes. You can save and edit the cluster data files to remove the trash clusters. An example of this method is given in [14].

The *number of harmonics* will depend on your research question. If you want to *see* a close representation of the actual EGG pulse shapes, 10 harmonics are usually needed. If you think that the feature you are investigating is a low-frequency phenomenon, or if you are mostly interested in the SampEn metric, then fewer harmonics will usually be enough.

3.5.2 Clustering in multiple passes

Because FonaDyn is a real-time program, it can not know anything at the START about what the data set as a whole is going to look like. This applies to recordings as well as to live signals. FonaDyn therefore has to adapt the clusters to the data as it goes along. This means that, on the first pass, the cluster colours early in the recording will not correspond to quite the same wave-shapes as late in the recording. Over time, the clusters will become stable, but initially, it helps if the variability in the first part of the signal is representative of that in the rest. Therefore it is a good idea to try to include excerpts from the full range of conditions as early as possible in a recording, and also to re-run the same signal using the cluster data from the first pass for initialization, as explained below.

3.5.3 Initializing the clusters

The outcome of the clustering is very sensitive to the first few cycles that are detected. There is usually some quiet before the subject starts phonating, which may cause some spurious 'cycles' to be detected in the background noise. Then, some of the initial centroids will be too far apart in their $3N$-dimensional space to describe EGG waveforms, and most subsequent real EGG cycles will tend to be 'captured' by the one or two 'random' centroids that happen to best describe EGG signals. We are trying to find an automated solution to this.

For the time being, there are two workarounds. The first is to wait until the subject is phonating 'normally', or in one of the experimental conditions, and then press the button **Reset counts**. From the EGG waveform at that moment, this will generate equal 'seed' centroids that soon drift apart from one another. The end result, however, will depend somewhat on exactly *when* the **Reset counts** is pressed. The final outcome will however become quite stable if you record the signals and make a second or even a third pass over the data, using the setting **Init: Pre-learned** (without pressing **Reset counts** or **Unload** in between).

The other workaround, when analyzing pre-recorded files, is to edit out leading pauses from the signal, such that it starts immediately at medium voice amplitude. In this way, the analysis will start out 'seeded' with similar waveshapes in *all* clusters, which soon diverge as the signal changes.

3.5.4 Rearranging clusters

Another issue of initialization is that the algorithm's allocation of cluster numbers to different EGG waveshapes is necessarily arbitrary. Since each cluster number is assigned a different display colour, this means that the cluster *colours* are unlikely to be the same every time, when a recording protocol is repeated in the learning phase. Once the learning can be turned off, as for classifying signals, this is no longer a problem.

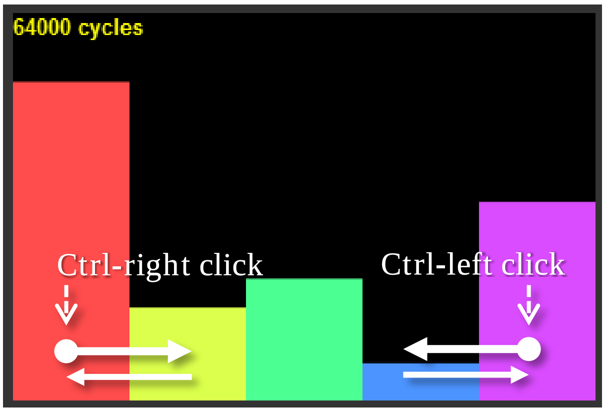


Figure 13.
You can change the cluster order by swapping the positions of two clusters at a time. Since this is a swap, repeating a click in the same place will undo the change.

To make your figures consistent, you may wish to re-arrange the cluster order. This can be done only when FonaDyn has stopped. *Ctrl*-click left or right on the cycle-count columns (Figure 13). Two adjacent clusters are then swapped, as shown here. Repeat this until you have achieved the desired order. The first and last clusters are also treated as adjacent; the order 'wraps around.' The cluster colors in the VRP are also updated.

Cluster data are saved to files of type `*_clusters.csv`. Another way to rearrange clusters is to edit those files, using a spreadsheet program, to rearrange the data clusters into the order that suits your application (see Figure 11). A tip is first to colour the text on each *row* to a sequence of colours similar to those shown in FonaDyn's bar graph (Figure 6). It is then somewhat easier to rearrange manually those rows into the sequence that you want (for instance, from weak to strong phonation). With this method, you can also *remove* a cluster that you don't want, simply by deleting that line. When done, save the `_clusters.csv` file, and reload it into FonaDyn.

3.5.5 SampEn parameters

The SampEn analysis is still somewhat experimental, so we have given you access to all the settings, to try out. It has three parameters: Tolerance, Window and Length, which can be set to different values for the harmonic levels and the phases. See the theory section 2.6.

3.5.6 Analyzing from multiple takes or multiple files

This subsection applies to FonaDyn 1.5.1 and higher. By default, FonaDyn clears the current cluster data and the VRP data when you press START. If you want instead to continue accumulating recordings into the current data, check the box **Keep data** that is to the left of the START button. The **Keep data** option could be appropriate for a long acquisition protocol, during which a subject needs to pause, or for analysing a batch of multiple input files for which the results should be combined into one VRP. In most cases, you will also want to choose the clustering setting **Init: Pre-learned**. Choose **Learning: On** to continue the same clustering operation across input takes or files. Choose **Learning: Off** to classify all the input files using one fixed clustering (which must first be **Load**ed).

3.6 Known problems

FonaDyn version 1.5.0 has the following known issues.

1) **Limited record time**. After 5-10 minutes of continuous operation, the FonaDyn graphics may start to slow down, become jerky, and eventually even stop; especially on computers with modest performance. A clear symptom is the row of green numbers at the bottom right of the SCIDE: if they intermittently flash white, then the program is slowing down too much. We believe that this behaviour is due to a problem internal to SuperCollider 3.x and its mechanism for “garbage collection” of disused software objects in memory; more specifically, to inconsistent handling of its internal so-called ‘grey list’. We can only hope that it will be fixed by the SuperCollider community, in a future release.
2) **CPU load**. The higher the fundamental frequency, the more EGG cycles have to be handled every second. In the high soprano range, FonaDyn may struggle noticeably to keep up, unless the computer is quite fast. The display may update less smoothly, in fits and starts.
3) Occasionally, with file input and/or output, FonaDyn will **fail to start or stop** properly. This is often due to a format error in the input file (did you choose the right file?), but also to inter-process handshaking errors, or network delays. Working with all files on a local hard disk is usually best. In the stopped state, by design, the START button displays “START”. In the running state, it displays “STOP”. After a successful but longish run, it may take up to a minute for FonaDyn to go from “Stopping...” to the really stopped state – just be patient. This symptom is related to problem (1) above. If the START button refuses to re-appear, close the main window, and invoke `FonaDyn.run` once more, perhaps also with action (4) below. Before you do that, it may be possible to save cluster data and VRP data even when the program is in a waiting state.
4) It may happen that the **server process is orphaned**, that is, SCSYNTH loses its connection with SCLANG. The solution is go to the SCIDE window and invoke the command **Kill All Servers** from its **Language** menu (or `Server.killAll`), and then start again.
5) Specifying the highest numbers of clusters and harmonics (up to 20, 20) may cause SCSYNTH to complain that the connection diagram becomes too complex. (To

appreciate this, you might look at the file Signal-code-diagram.pdf.) If you really want that many, this can be allowed by saving into the SC startup file the line

```
Server.local.options.numWireBufs = 256;  // the default is 64
```

Now, restart SuperCollider, and you will probably be able to run up to the maximum. The rainbow graphs are pretty, but remember that with 20 harmonics, you are limited to f_0 values of less than 10000/20 = 500 Hz (section 2.4.1).

SuperCollider versions up to 3.9.0 have the following known problem: on *very* fast computers, the SCIDE may fail to start up properly. Its Help docklet displays “Sending request...” indefinitely, and the interpreter does not become operative. This problem is due to an inter-process synchronization bug that is known to SuperCollider’s developers, and hopefully will be resolved soon.

Acknowledgments

FonaDyn is written in SuperCollider [2], an interactive real-time audio and music processing environment, first created by James McCarthy. SuperCollider is cross-platform (Windows, Mac, Linux, iPhone) and open-source freeware. The foundation version of FonaDyn was written in 2015 by Dennis Johansson as his M.Sc. degree project in Computer Science [11]. Isak Nilsson, in the course of *his* M.Sc. degree project [14], ran tests on Mac OSX, recompiled the *PitchDetection* UGens for OSX, and contributed supporting Matlab code. FonaDyn continues to be developed by Ternström and co-workers. The work was partially funded by the Swedish Research Council (Vetenskapsrådet), project 2010-4565.

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