NEW SONIFICATION TOOLS FOR EEG DATA SCREENING AND MONITORING

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ABSTRACT

This paper describes two software implementations for EEG data screening and realtime monitoring by means of sonification. Both have been designed in close collaboration with our partner institutions. Both tools were tested in depth with volunteers, and then tested with the expert users they are intended for, i.e. neurologists working with EEG data. In the course of these tests, a number of improvements to the designs were realised; tests and the final versions of the tools are described in detail. The scope of the paper is intended to provide an integrated description and analysis of all aspects of the design process from sonification design issues to interaction choices to user acceptance.

[Keywords: EEG data sonification, sonification design, user interaction design]

1. INTRODUCTION

At our neurological partner institution, two routine tasks come up in everyday work where sonification is potentially useful: Fast screening of long-time EEG recordings, and realtime monitoring during EEG recording sessions.

1.1. EEG Background

As this is covered extensively in a number of other papers [1, 2, 3, 4], this is very brief here. EEG is short for electroencephalogram, i.e. the registration of the electrical signals coming from the brain that can be measured on the human head.

For this paper, the two most important things to know are:

Firstly, there are standard systems where to locate electrodes on the head, called montages; e.g. the so-called 10-20 system, which spaces electrodes at similar distances over the head (see e.g. [5] and many other textbooks).

Secondly, the signal from a single electrode is often analysed in terms of its characteristic frequency band components: The useful frequency range is typically given as 1-30 Hz, sometimes extended a little higher and lower. Within this range, different frequency bands have been associated with particular activities and brain states; e.g. the 'alpha' range is between 8 and 13 Hz, associated with general state of relaxedness, and non-activity of the brain region for visual tasks; it is most prominent with eyes closed.

For both sonification designs presented, we split the EEG signal into frequency ranges which closely correspond to the traditional EEG bands; we decided to use constant relative bandwidths of one octave each to attain a more equal energy balance between the bands. The ranges are: *deltaL(ow)* from 1 - 2 Hz, *deltaH(igh)* from 2 - 4 Hz, *theta* from 4 - 8 Hz, *alpha* from 8 - 16 Hz (this is a bit wider than the traditional value of 13, and includes the mu-rhythm band), *beta* from 16 - 32 Hz, and *gamma* from 32 - 64 Hz.

1.2. Rapid Screening of Long-Time EEG Recordings

For a number of neurological problems, it is standard practice to record longer time stretches of brain activity. A stationary recording (as made at our partner institution) usually lasts more than 12 waking hours; night recordings usually are longer, up to 36 hours. For people with so-called 'absence' epileptic seizures (often children), recordings with portable devices are made over similar stretches of time. These recordings are then visually screened, i.e. looked through in 20-30 second frames at a time; this process is both demanding and slow.

For the particular application toward 'absences', rapid auditory screening is ideal: these seizures tend to spread over the entire brain, so the choice of which electrodes to screen acoustically is not very risky; furthermore, the seizures have quite characteristic features, and are thus relatively easy to identify quickly. For more general screening, finding time regions of interest quickly (by auditory screening) potentially reduces workload and increases overall security. With visual and auditory screening combined, the risk of not noticing important events in the recorded brain activity is reduced.

1.3. Realtime Monitoring during EEG Recording Sessions

A second scenario that benefits from sonification is realtime monitoring while recording EEG data. This is a long-term attention task: an assistant stays in a monitor room next to the room where the patient is being recorded; s/he watches both a video camera view of the patient, and the incoming EEG data on two screens. Realtime uses of biosignals have other applications too, see e.g. [6, 7]. In the event of atypical EEG activity (which must be noticed, so one can intervene if necessary), a patient may or may not show peculiar physical movements. Thus watching the video camera, one can miss atypical EEG activity for a while.

Here, sonification is potentially very useful, because it can alleviate constant attention demands: One can easily habituate to a background soundscape, which is known to represent 'everything is normal'. When changes in brain activity occur, the soundscape changes (in most cases, activity is increased, which increases both volume and brightness), and this change in the acoustic environment automatically draws attention.

A sonification design that aims to render EEG data in real time is also useful for studying brain activity as recorded by EEG devices at its natural speed: One can easily portray activity in the
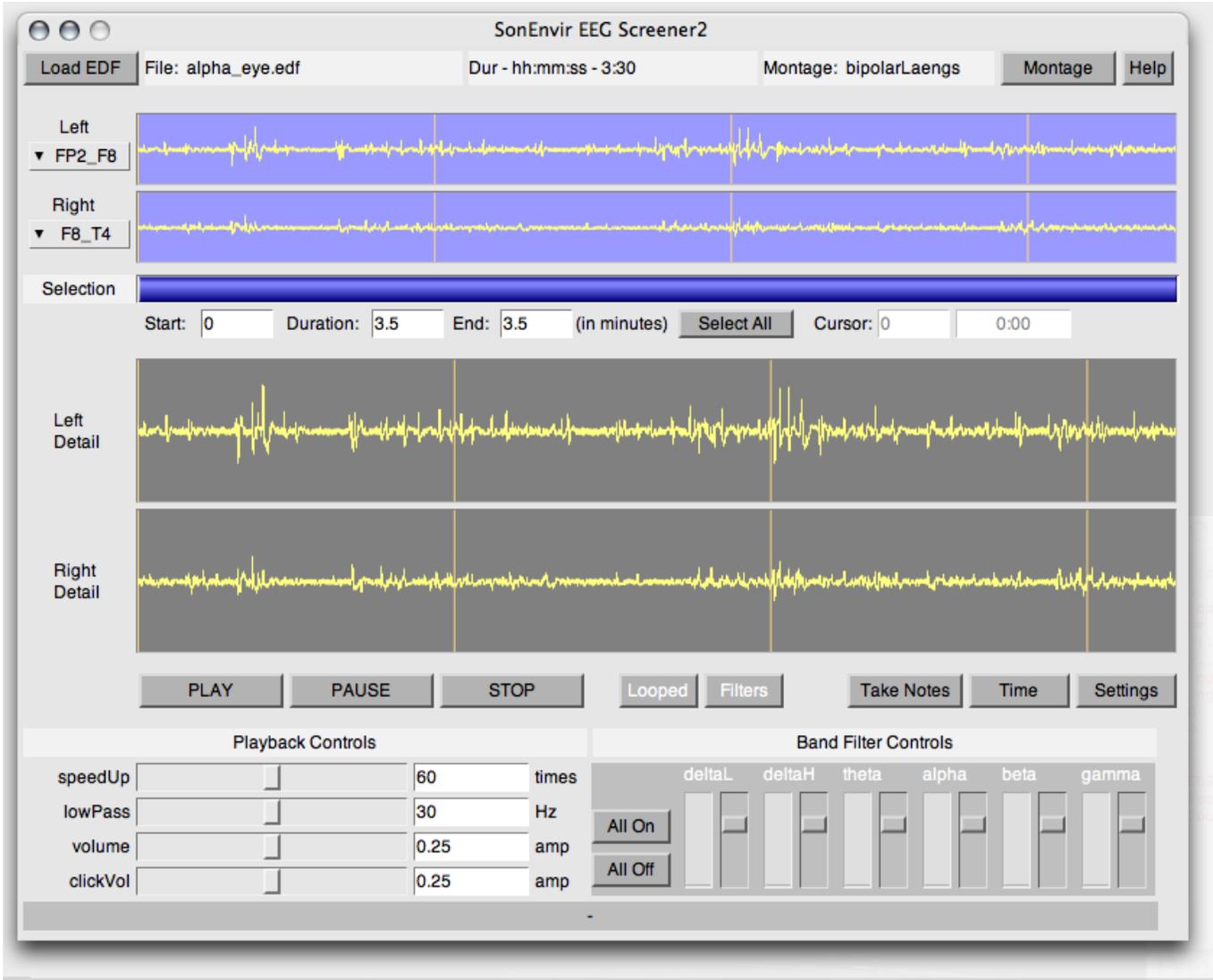
Figure 1: *The EEGScreener GUI.*

traditional EEG frequency bands acoustically; as many of the phenomena are described as rhythmical, auditory presentation is particularly appropriate here [8].

Thus the implementation of this tool is in two stages:

Stage one is a data player, which plays recorded EEG data files at realtime speed with the same sonification design (and the same adjustment facilities) as the final monitor application. This allows for learning the range of sounds the system can produce, and to find settings which work well for a particular situation and user.

Stage two is an add-on to the software used for EEG recording, diagnosis, and administration of patient histories at the institute. Currently, this stage is implemented as a custom version of the EEG recording software which simulates data being recorded now (by reading a data file), and sending the 'incoming' data by network on to a special version of the Realtime player (i.e. the sound engine and interface). Here, the incoming data is rendered into sound as in the player-only version. Eventually, this second program should be implemented within the EEG software itself,

but this will be done only after tests have concluded.

1.4. Overview

The sonification design and user interface of EEGScreener application is described in detail in section 2; the details of the EEG-RealTimePlayer are given in section 3. Section 4 reports on two rounds of tests we have conducted with expert users, and section 5 presents conclusions. Both applications have been realised in the SuperCollider programming environment [9].

2. THE EEG SCREENER

2.1. Sonification Design

For rapid EEG data screening, there is little need for an elaborate sonification design: As the signal to be sonified is a time signal, and a signal speed of some 10000s of points per seconds

is deemed useful for screening, straightforward audification is the obvious choice, as it allows for keeping the rich detail of the signals entirely intact. With sampling rates around 250 Hz, a typical speedup factor is 60x faster than real time, which transposes our center band (alpha, 8-16Hz) to 480-960 Hz, well in the middle of the audible range. For more time resolution, one can go down to 10x, or for more speedup, up to 360x.

This allows for wide range of time scales of local structures in the data to be put into the optimum time window (the ca. 3 seconds of echoic memory) [10], while keeping the inner EEG bands well in the audible range; if needed, one can compensate for reduced auditory sensitivity to the outer bands by raising their relative amplitude.

A lowpass filter is available from 12 to 75 Hz, default at 30 Hz, to provide the equivalent of visual smoothing used in EEG viewer software. Our users wished for that, and it is a simple way to reduce higher band activity, which is mostly considered noise.

A choice is provided between the straight audified signal, and a mix of six equal-bandwidth layers, which can all be individually controlled in volume. This allows both for focused listening to individual bands of interest, and for identification of the EEG band a particular audible component belongs to.

2.2. Interface Design

The task analysis for the Screener demanded the graphical user interface to be simple to use (low-effort, little training needed), error-free, fast, and to provide for keeping reproducible results. Furthermore, it should provide rich choices of what to listen to, and detailed visual feedback of what exactly one is hearing how. For quick experiments and learning, a sample file is loaded automatically. The GUI elements and their functions are:

2.2.1. File, Electrode, and Range Selection

The button *Load EDF* is for selecting a file to be screened. Currently, only .edf files are supported, but other formats are easy to add if needed. The text views next to it (top line) provide file data feedback: path name, duration, and montage type the file was recorded with[1]. The button *M*ontage opens a separate GUI for choosing electrodes by location on the head (see figure 2), and the Help button opens an extensive help page (in German).

The popup menus *Left / Right* provide a choice of which electrode to listen to on the two audio channels used. The signal views *Left / Right* show an overview of the signal for the entire length of the chosen electrodes. With short files, the vertical marks are minutes, with longer files, hours. During screening, the current playback position is indicated by a vertical cursor.

The range slider *Selection* allows for selecting a range with-in the entire file to be screened. The number boxes *Start, Duration, End* show the current selection properties, and the values can also be set numerically from here. The button *Select All* selects the entire file. The number box *Cursor* shows the current playback position in minutes and also as hours:minutes:seconds.

The signal views *Left Detail / Right Detail* show the waveform of the currently seleced electrodes in detail, zoomed for the current selection. During screening, the current playback position is also indicated here by a vertical cursor.

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[1]As edf files do not store montage information, this is inferred from the number of EEG channels in the file; at our institution, all the raw data montage types have different numbers of channels
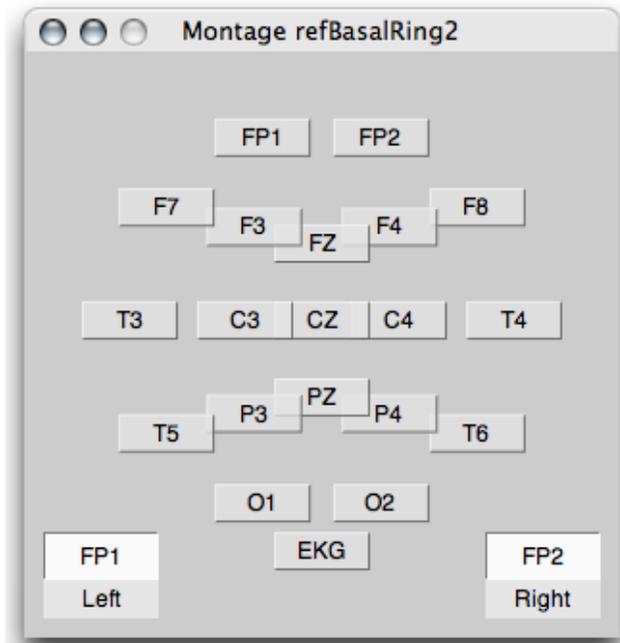

Figure 2: *The Montage Window, allowing for electrode selection by location. One can drag the light gray labels and drop them on the white fields 'Left' and 'Right'.*

2.2.2. Playback and Note Taking

The buttons *Play, Pause, Stop* start, pause, and stop the sound.

The button *Looped/No Loop* switches between once-only playback and looped playback (with a click to indicate when the loop restarts). The button *Filters/Bypass* switches playback between Bypass (the straight audified signal, only low-pass-filtered), and Filters, the mixable band-split signal.

The button *Take Notes* opens a new text window for taking notes during screening. The edf file name, selected electrodes and time region, and current date are pasted in as text automatically.

The button *Time* adds the current playback time at the end of the notes window's text, and the button *Settings* adds the current playback settings (see below) to the notes window text.

While the notes window is in front, three key shortcuts are available such that one never needs to leave the notes window while screening a file: one can add current time as text, add current settings, and pause/resume playback (e.g. to finish typing a note).

2.2.3. Playback Controls

These control the parameters of the screener's sound synthesis.

speedUp sets the speedup factor, with a range between 10-360; the default value of 60 means that one minute of EEG is presented within one second. Note that this is straightforward tape-speed acceleration; this preserves full signal detail. The option to compare different time-scalings of a signal segment allows for learning to distinguish mechanical (electrode movements) and electrical artifacts (muscle activity) from EEG signal components.

lowPass sets the cutoff frequency for the lowpass filter, range between 12 and 75 Hz, with a default of 30 Hz.

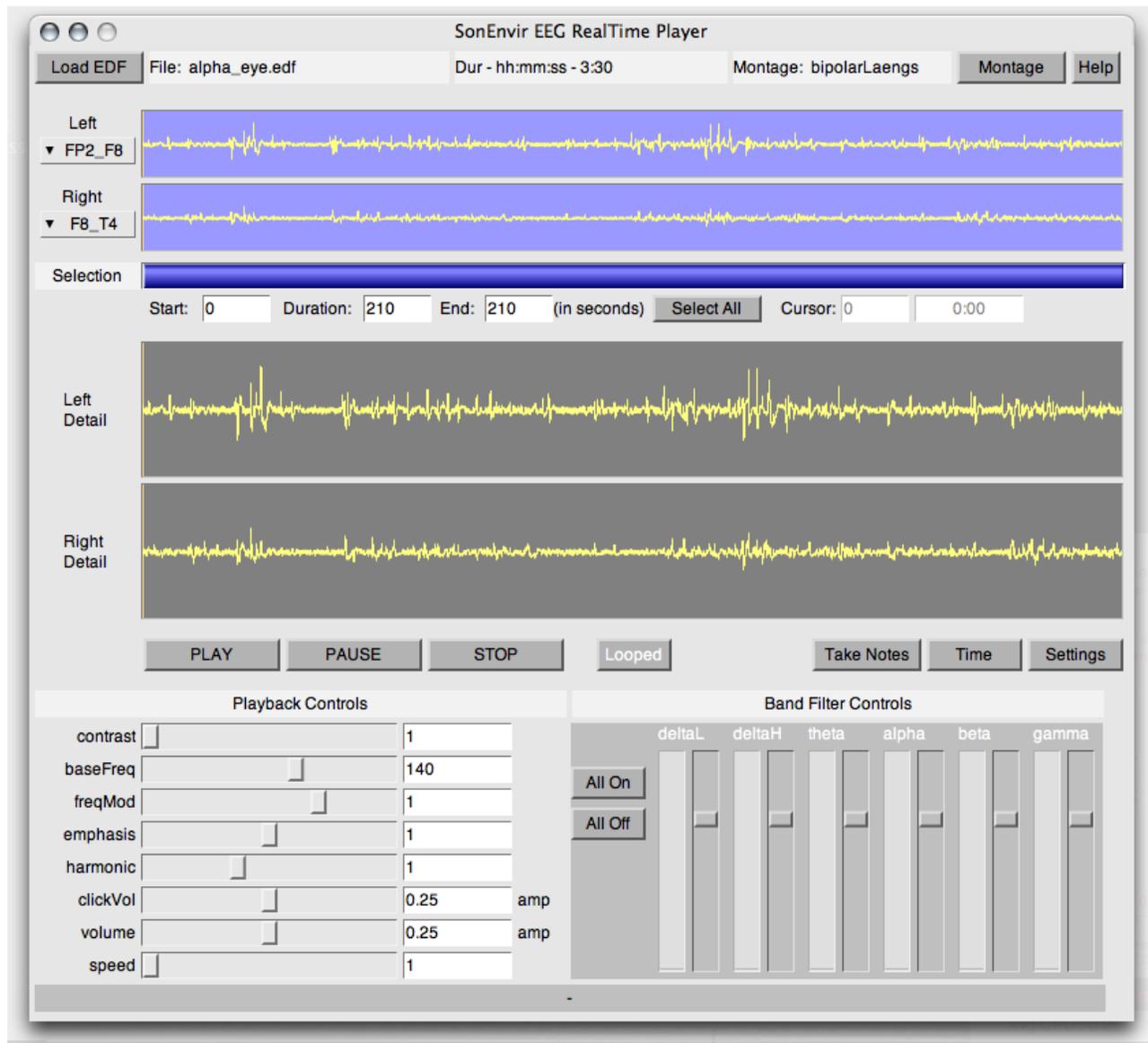*clickVol* sets the volume of the loop marker click.

Figure 3: *The EEG Realtime Player GUI.*

volume sets the overall volume.

2.2.4. Band Filter Controls and Views

In Bypass mode, only the meter views are visible in this section, and they display the amount of energy present in each of the six frequency bands (deltaL, deltaH, theta, alpha, beta, gamma).

In Filters mode, the controls become available, and one can raise the level of bands one wants to focus on, or turn down bands that distract from details in other bands.

The buttons *All On / All Off* allow for quickly setting all levels to medium or zero.

3. THE EEG REALTIME PLAYER

The EEGRealtimePlayer allows for listening into details of EEG data in real time (or up to 5x faster), in order to follow temporal events in their original rhythmic contour. An extension toward monitoring during EEG data recording sessions is realised in a separate prototype but not yet integrated into the Realtime player.

3.1. Sonification Design

The sonification design for real time monitoring is much more elaborate than the screener. It was prototyped by R. Hoeldrich in MATLAB, and then implemented for realtime interactive use in SuperCollider by A. de Campo.

The EEG signal of each channel listened to is split into six

bands of equal relative bandwidth (one octave, 1-2, 2-4, up to 32-64 Hz), largely following standard EEG terminology. Each band is sonified with its own oscillator and a specific carrier frequency: based on a user-accessible fundamental frequency *baseFreq*, the carriers are by default multiples of *baseFreq* by 1, 2, .. 6. If one wants to achieve more perceptual separation between the individual bands, one can deform this overtone pattern with a stretch factor *harmonic*, where 1 is pure overtone tuning:

$$carFreq = baseFreq * i * harmonic^{i-1} \qquad (1)$$

The carrier frequency in each band is also modulated with the band-filtered EEG signal, thus creating a representation of the signal shape details as deviation from center pitch; the modulation depth is called *freqMod*. The amplitude of each oscillator band is determined by the amplitude extracted from the corresponding filter-band, optionally stretched by an expansion factor *contrast*; this creates a stronger foreground/background effect between low-energy bands and bands with more activity.

For realtime monitoring as a background task, an additional option for emphasis exists: high activity levels activate a sideband modulation at *carFreq * 0.25*, which creates a new fundamental frequency two octaves lower. This should be difficult to miss.

Finally, for file playback, crossing the loop point of the current selection is acoustically rendered as a bell-like tone.

3.2. Interface Design

Most elements (buttons, text displays and signal views) have the same functions as in the EEGScreener; this overlap is intended to reduce learning time for medical personnel using both applications. The main differences to the EEGScreener are: the default time unit is seconds here, not minutes (because this is the more convenient unit for realtime sonification); there is no button "Filters/Bypass" (because there is no meaningful unfiltered signal to listen to); and there are many more playback controls, since the sonification model (as described above) is much more complex.

3.2.1. Playback Controls

These controls are ordered by importance from top to bottom:

contrast ranges from 1-4; values above 1 expands the dynamic range, making active bands louder and thus moving them to the foreground relative to average-activity bands. For background monitoring, levels from 2-3 are recommended.

baseFreq is the fundamental frequency of the sonification, between 60-240 Hz; this can be tuned to user taste - and our users have expressed strong personal preferences for their choice of *baseFreq*.

freqMod is the depth of frequency modulation of the carrier for each band. At 0, one hears a pure harmonic tone with varying overtone amplitudes, at greater values, the pitch of the band swings up and down with activity in that band. 1 is normal deviation.

emphasis adds a pitch two octaves lower for very high activity; this can be used for extra emphasis in background monitoring.

harmonic is the harmonicity of the carrier frequencies: A setting of 1 means purely harmonic carrier frequencies, less compresses the spectrum, and more expands it; this can be used to achieve better perceptual band separation.

clickVol sets the volume of the loop marker click.

volume sets the overall volume of the sonification.

speed controls an optional speedup factor for file playback, with a range between 1-5, 1 being realtime; in live monitoring mode, this control will be disabled.

3.2.2. Band Filter Controls and Views

The buttons "All On" / "All Off" allow for setting all levels to medium or zero. The meter views show the amount of energy present in each of the six frequency bands, and the sliders next to them set volume of each frequency band.

4. USER TESTS

4.1. Test EEG Data

For development and testing of the sonification players described, a collection of EEG recordings - containing typical epileptic events and seizures - was arranged. This database was assembled at the Department for Epileptology and Neurophysiological Monitoring (University Clinic of Neurology, Medical University -...-), by using the in-house archive system. It contains anonymous data of currently or recently treated patients.

For the expert users tests, three data examples were chosen, suited for each player's special purpose. For the Screener, rather large data sets were selected, to test the quick screening use of this tool. Two measurements of absences and one day/night EEG of seizures localized in the temporal lobe were prepared. The Realtime Player was tested with three short data files; one a normal EEG (incl. eye movement artefacts), and two pathological EEGs (generalized epilepsy potentials, fronto-temporal seizure).

The experts we worked with considered the use of audition in EEG-diagnostics very unusual. We expected them to find it difficult to associate sounds with the events, so they did some preliminary sonification training: For all data examples, they could look at the data with their familiar EEG-viewer after having listened first, and try to match what they heard with the graphical curves.

4.2. Initial pre-tests

An initial round of tests was done to get a first impression of usability, and data appropriateness, which also contained experimental tasks (learning to listen). For getting independent and unbiased opinions, two interns were invited to test versions 1 of the screening and realtime players by listening thru the entire prepared database at their own pace. They were instructed to take detailed notes of the phenomena they hear, and where in which files; and they spent roughly 40 hours on this task. This documentation of their listening experiments was then verified in internal re-listening and testing sessions. We could then reduce some parameter ranges to prevent extreme settings, and select appropriate data sets for the second test round with expert users.

4.3. Tests with expert users

As the eventual success of these players depends on acceptance by the users in the clinical setting, it was essential to do an evaluation with medical specialists. This was done by two feedback trials. Using the results of the primary expert test round, the players were then improved in many details. For both players we made pre/post-comparisons between the different versions.

While we tested with the complete potential user group at our partner institution, a test group is rather small (n=4); thus we consider the tests (and especially the open question/personal interviews section) more qualitative than quantitative data.

To prepare the four specialists (of the Department for Epileptology and Neurophysiological Monitoring) for their separate test sessions, they were introduced all together in the new aspects of

data evaluation and experience by sonification. For each data-player a separate test session was scheduled to avoid acoustic 'over-load' and potential confusion.

4.3.1. Questionnaire

The questionnaire contained the following 11 scales:

1. Usability
2. Clarity of Interface
3. Visual design
4. Adjustability of sound (to individual taste)
5. Freedom of irritation (caused by sounds)
6. Good sound experience (pleasing)
7. Allows for concentration
8. Recognizability of relevant events in data by listening
9. Comparability (of observations) with EEG-Viewer software
10. Practicality in Clinical Use
11. Overall impression (personal liking)

The ratings to give for each statement ranged from 1 (strongly disagree) to 5 (strongly agree). In addition to the 12 standardized questions, space for individual documentation and data description was provided. Moreover, an open question allowed for further comments, observations, and suggestions.

4.4. Results

The initial round of tests resulted in a number of improvements in both players: Elaborate EEG waveform display and data range selection was added to both; the visual layout was unified to emphasize elements common to both players; and the screener was extended with band filtering, which is both useful and a good mediating step toward the more complex realtime sonification design.

4.4.1. Analysis of user tests Screener Version 1 vs. 2

By optimizing the interface and interaction possibilities, version 2 of the Screener offers more comfortable use (+0,34) and more attractive visual design (+0.5) The sound experience of the medical specialists has improved much (+1.25), and the experienced irritation has decreased by an even larger amount (1.63). While all other criteria improved substantially, recognizability of events, comparability with viewer software, and clinical practicality got lower ratings (between -0.5 and -0.75). We suspect that the better rating in the first test round may have been enthusiasm about the novelty of this tool. Thus, personal conversation with the expert users after the tests showed how strongly opinions differed: One user did not feel 'safe' and comfortable with the screener and could not trust his own hearing skills enough to discriminate relevant information from artefacts. By contrast, the three others were quite relaxed and felt positively reassured to do the listening properly and effectively. Furthermore, the users probably were less motivated in comparing the EEG viewer to the listening result (which was asked in one question), as they carefully did that in the first tests already.

Nevertheless, all users reported much higher overall satisfaction with version 2 of the screener (+0,62).

The answers in the open comments section can be summarized thus: All users confirmed better usability, design, clarity and
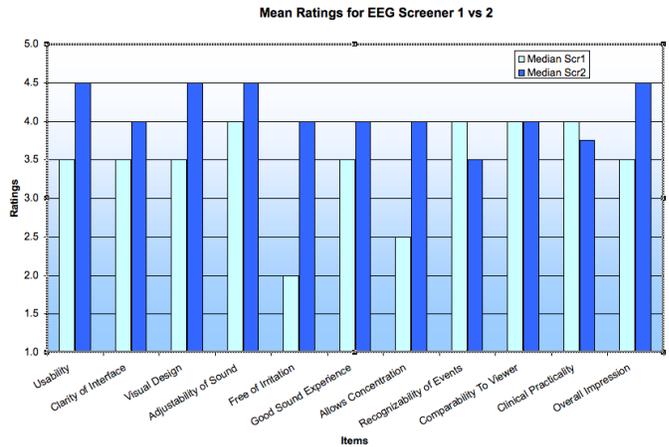

Figure 4: *The ratings for both screener versions.*

transparency of version 2. Some improvements were suggested in the visualization of the selected EEG channels, in particular when larger files are analysed. Moreover, integration of the sonification into the real EEG viewer would be appreciated a lot. A plug-in version of the player for the EEG-Software used (NeuroSpeed by B.E.S.T. medical) was already in preparation before the tests; in effect, the expert users confirmed its expected usefulness.

4.4.2. Analysis of usertests RealtimePlayer Version 1 vs. 2

The mean estimation of the second realtime player version shows a positive shift in nearly all contents of the questionnaire. Moreover the range of the ratings is smaller than before, so the answers were more consistent. The best ratings were given for visual design (+1), adjustability of sound (+1) and comparability to viewer (+1,5), all estimated with "good to very good". The overall impression is now estimated as good (+1), as well as usability (+0,5), clarity of interface (+0,5), good sound experience (+1), recognizability of relevant EEG events (+1) and practical application (+1) are estimated similarly satisfying. The only item that keeps the same mean rating is freedom of irritation, estimated as a little better than mean. The same rating was given for allowed concentration (+1,5), which has improved very much.

Probably, these two aspects correspond to each other: in spite of the improved control of irritating sounds and a learning effect, the users were still untrained in coping with the rather complex sound design. This sceptical position was taken in particular by two users, affecting items 5 to 9. All in all, the ratings indicate good progress in the realtime player's design.

Comparing the ratings across the two first versions, the Realtime Player 1 was not rated as highly as the Screener 1. We attribute this to the higher complexity of the sound design (which did not come across very clearly under the time pressure given), the related non-transparency of some parameter controls, and to ensuing doubts about the practical benefit of this method of data analysis. Only the rating for irritation is better than Screener 1, which indicates that the sound design is aesthetically acceptable.

All these concerns were addressed in Realtime Player v.2:

In order to clarify the band-splitting technique, GUI elements indicate the amount of power present in each band, and allow for interactive choice of which bands to listen to; less parameter
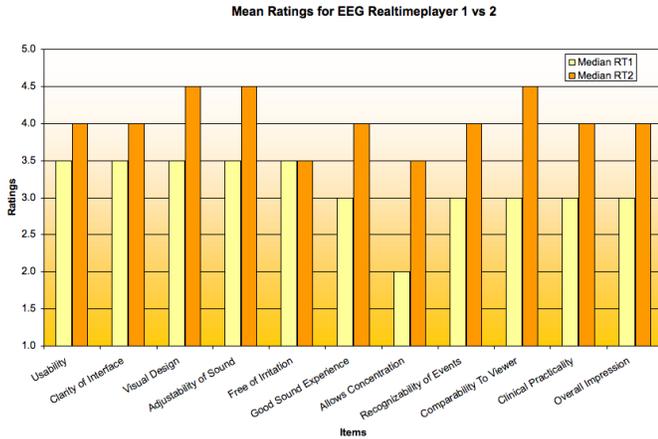
Figure 5: *The ratings for both RealtimePlayer versions.*

controls are made available to the user[2], with simpler and clearer names. Much more detailed help info pages are also provided now.

Finally, band-splitting (adapted to audification) was integrated into the screener v2 as well, which gives users a clearer understanding of this concept across different sonification approaches.

4.4.3. Qualitative results for both players (version 2)

For both players, all users mentioned easy handling (usability), good visual design, and transparency of functionality. More positive comments on the Screener were "higher creativity" (by using the frequency controls) and that irritating sounds have nearly disappeared. One user explained this by a training effect, and we agree: It seems that as users learn to interpret the meaning of "unpleasant" sounds (such as muscle movements), the irritation disappears. Regarding the realtime player, users mentioned good visual correlation with the sound, because of the new visual presentation of EEG on the GUI. One user noted that acoustical side-localisation of the recorded epileptic seizure works well.

Further improvements were suggested: For both players, the main wish is synchronization of sound and visual EEG representation (within the familiar software): In case of realtime monitoring, this would allow to better compare the relevant activities. As far as screening is concerned, the visual representation of larger files on the GUI was considered not satisfying.

For the realtime player, presets for the complex parameters in accordance to specific seizure types were suggested as very helpful. Moreover, usability could still be improved a bit more (no specifics), as well as irritating sounds should be further decreased. This wish may also be due to the fact that the offered parameter-controls for reducing disturbing sounds may not have been used fully. This could be addressed by more training.

5. CONCLUSIONS

According to the experts' evaluation of the EEG Screener, intensive listening training will be essential for its effective use in clinical practice - in spite of improved usability and acceptance of the second version. As the visual mode in clinical EEG diagnostics

and data analysis is still dominant, for the widespread use of sonification tools an alternative time and training management is necessary. After such training, our new tools may help to successively reduce effort and time in data analysis, decrease clinical diagnostic risk, and in the longer term, offer new ways of exploring the EEG.

6. FUTURE WORK

A number of steps to be taken next are clear already:

For the Realtime Player, the top priority is integration of the network connection for realtime monitoring during EEG recording sessions. Then, user tests in real world long-term monitoring settings can be conducted. These tests should result in recommended synthesis parameter presets for different use scenarios.

For the sound design, we have experimented with an interesting variant which emphasizes the rhythmic nature of the individual EEG bands more (see [8, 6]). This feature will be made available as an additional user parameter control ('rhythmic'), with a value of 0 keeping the current sound design as is, and 1 accentuating the rhythmic features strongly.

For both Realtime Player and Screener, we plan for eventual integration into the EEG administration software used at our clinic once the design work is finalized.

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[2]Version 1 had some visible controls mainly of interest to the developer.