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EEG analysis in a telemedical virtual world

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Abstract

Telemedicine creates virtual medical collaborative environments. We propose here a novel concept of virtual medical devices (VMD) for telemedical applications. VMDs provide different views on biomedical recordings and efficient signal analysis. In this paper we present a telemedical EEG analysis environment based on virtual reality technologies. The same EEG signal/recording could be viewed either as a waveform or as animated topographic maps on a 3D head model. In addition to visualization, sonification is used as a secondary presentation modality. The environment is based on a VRML head model animated with Java applets, and allows the use of standard web browser. ©1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

In the conventional metaphor of health care services the physical presence and collaboration of physicians, medical staff, and the patient was prerequisite. The health care trend is now to provide the latest available information technology to all segments of the urban, rural, city and community centers. Moreover, globalization and higher people mobility (business, tourism, etc.), leads to fragmented care delivered at scattered locations. As a consequence, usual limitations are:

– lack of patient medical record (PMR);
– absence of a qualified physician;
– requirement of a specialist team;
– lack of sophisticated medical equipment.

Increased performance of information infrastructure facilitates real-time execution of applications, establishing a basis for a new medical discipline “telemedicine” [4]. In addition to improved health care by telepresence, telemedicine can create new service by creating virtual collaborative environments, independently of the participants’ physical presence.

In this paper we present a telemedical environment for EEG analysis based on web and virtual reality (VR) technologies. Section 2 presents web based telemedical applications and in Section 3 we introduce virtual medical devices (VMD) as a novel approach making possible flexible views of medical recordings. The availability of multimedia and virtual reality (VR) technology has made possible multimodal data presentation. The basic characteristics of multimodal presentation are given in Section 4. The multimodal EEG viewer *mmViewer* is presented in Section 5, while lessons learned in the development of an EEG analysis environment are given in Section 6.

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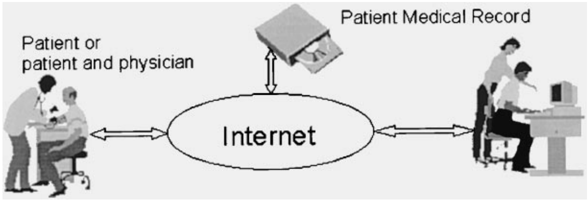

Fig. 1. Web based virtual medical world.

2. Telemedical applications in Internet environment

Telemedicine significantly changes storage, retrieval, and use of biomedical information in medical information systems. The evolution of medical information systems is greatly influenced by the capabilities and price/performance ratio of novel information technology. The internet and world wide web (WWW) as a global information infrastructure offers a low cost environment for telemedical applications [17]. It seems that at the present state of technology, web based medical applications represent a natural way of creating interactive collaborative environments, namely a virtual medical world (VMW), as depicted in Fig. 1.

Telemedicine creates virtual environment for collaboration between multiple physicians, medical staff and the patient, independently of their physical presence [13]. Therefore, high-quality medical services become available for distant patients and urgent cases. As an example of an existing telemedical environment for EEG analysis *teleEEG* is developed at the University of Calabria. This system gives the possibility to manage local patient database, including EEG data files. It is based on point-to-point communication using a standard telephone line [21].

Web based medical information systems should initiate and maintain virtual medical worlds ad hoc on specific participant request. They must allow maximum flexibility for data acquisition and exploration. In our environment, EEG data acquisition is performed on the patient side. The data are then transferred and archived by data using a web infrastructure, into the patient medical record. We propose the use of standard data formats, such as ASTM for EEG. [1] Physician could then examine EEG data either on-line, in real-time during recording, or the off-line from archive. Finally, they could add their findings to the patient medical record.

[1] ASTM E1467-94 Standard Specification for Transferring Digital Neurophysiological Data Between Independent Computer Systems, American Society for Testing and Materials (ASTM).

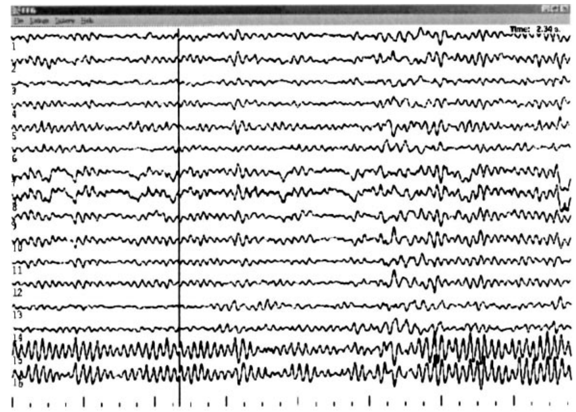

Fig. 2. Standard waveform view on EEG signal as default VMD.

3. Virtual medical devices

Diagnostic procedures often require different views of the same data set or medical recording. Therefore physicians should be able to choose the appropriate view they require, or easily change different views during analysis. We propose to perform an examination of the raw or derived data by using a set of virtual medical devices (VMD). Each VMD provides a specific view of the same record. As an example, during EEG analysis an electroencephalographer could choose a standard waveform to view the analyzed temporal changes, as given in Fig. 2. In addition, animated topographic maps on a 3D head model presented in Fig. 3 could be used to trace spatio-temporal changes of brain electrical activity. Although based on the same EEG record, they provide the flexibility of different views within the same diagnostic procedure.

A VMD has spatially distributed functions: I/O at patient side, processing (possible on all three sites), and presentation at the physician side. The physician could examine the same medical record (raw data) using different virtual medical devices, even simultaneously.

Our proposed approach is integrated into the web based medical information system *DIMEDAS* [16]. For each EEG recording in the patient medical record

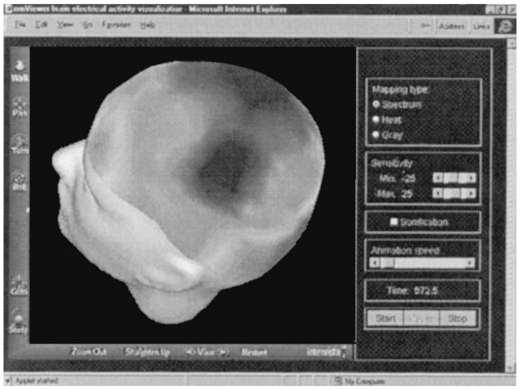

Fig. 3. *mmViewer* as VMD for animated topographic map presentation.

available VMD icons are displayed, as presented in Fig. 4. During an analysis an appropriate VMD is invoked by simply clicking on the chosen VMD icon associated with the selected recording.

4. Multimodal presentation

Multimodal presentation significantly improves quality of a VR environment. Bernsen proposes the model of human–computer interface with physical, input/output and internal computer representation layers [2]. A two-step transformation process is required for human–computer interaction. For the input those steps are *abstraction* and *interpretation*, and for the output they are *representation* and *rendering*.

Technology and tools for multimodal presentation are commercially available due to the progress of multimedia and VR hardware and software. However, multimedia and VR technology applied in human-computer interface does not guarantee successful presentation.

Conventional applications use unimodal presentation minimizing the use of resources to mediate the information. Simultaneous presentation of the same information in different modalities seems like a loss of resources. However, our natural perception is based on redundancy. Redundancy of human–computer interface should be realized using multimodal presentation. The main issue in the design of multimodal presentation is the level of redundancy. A low level of redundancy increases cognitive workload, while a high redundancy irritates the user. There is an appropriate measure of multimodal redundancy for a given application.

4.1. Visualization of brain electrical activity

Visualization provides significant support for understanding of complex processes. Possible insights into brain functions could be facilitated using visualization of brain electro-magnetic activity, observing either its electric component recorded on the scalp (EEG) or magnetic field in the vicinity of the head (MEG). In addition to EEG, that has been routinely used as a diagnostic tool, MEG is used to complete the picture of underlying processes. This is due to the fact that the head is almost transparent for magnetic fields, while its inhomogeneities (caused by liquor, skull, and skin) considerably influence EEG recordings.

Topographic maps of different parameters of brain electrical activity have been commonly used in research and clinical practice to represent spatial distribution of activity [6]. First applications used topographic maps representing the activity on 2D scalp projections from the top view. EEG brain topography is gradually becoming a clinical tool. Its main indication is to facilitate determination of brain tumors, focal diseases of the brain (including epilepsy, cerebrovascular disorders and traumas), disturbances of consciousness and vigilance, such as narcolepsy, intraoperative monitoring of brain function, etc. It is a valuable tool in neuropsychopharmacology estimating effects of drugs acting on the nervous system (hypnotic, psychoactive drugs, antiepileptics, etc.). In psychiatry, EEG brain topography has been used to identify biological traits of certain disorders such as depression and schizophrenia, early onset of Alzheimer disease, hyperactivity with or without attention deficit disorders in children, autism, etc. [6,15].

Recent advances in computer graphics and increased processing power provided the means of implementing 3D topographic maps with real-time animation. 3D visualization resolves one of the most important problems in topographic mapping – mapping distortion when projecting the scalp surface onto the plane. Other issues of topographic mapping are:
– interpolation methods;
– number and location of electrodes;
– score to color mapping.

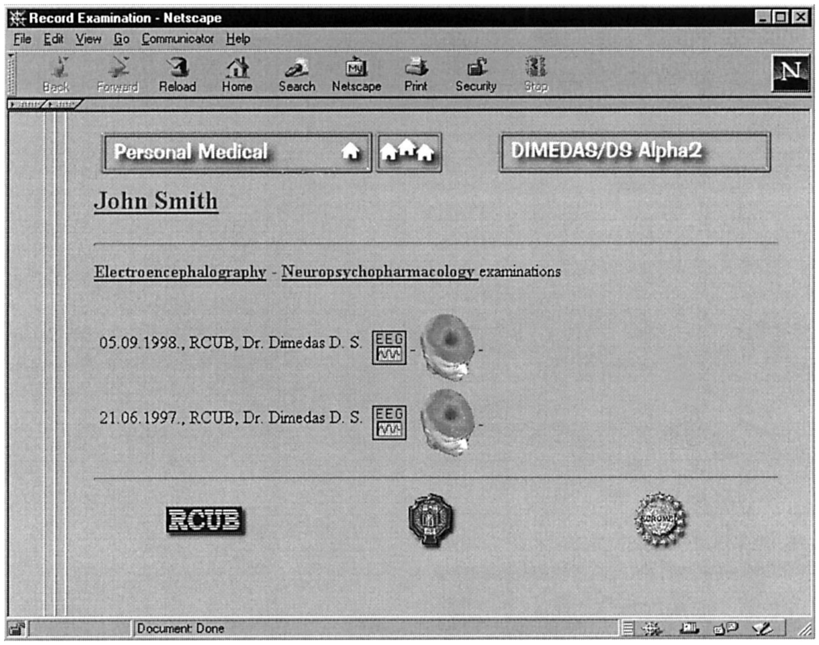

Fig. 4. EEG VMDs in *DIMEDAS* information system; two VMDs are associated with every EEG recording.

While in CT and PET images every pixel represents actual data values, brain topographic maps contain only values observed on electrode positions. Consequently, all the other points must be spatially interpolated using known score values measured on electrode positions. Therefore, higher number of electrodes makes more reliable topographic mapping possible. Electrode positions are usually predefined (like international 10–20 standard), although for some experiments custom electrode settings could be used to increase spatial resolution over certain brain regions. Finally, for color representation of data values different types of color LUT might be utilized. The most frequently used are spectrum (using colors of visible spectrum, from blue to red, as represented in Fig. 3) and heat (from black through yellow to white) [6].

Isochronous representation of observed processes preserves genuine process dynamics, and facilitates perception of intrinsic spatio-temporal patterns of brain electrical activity. However, animation speed depends on perceptual and computational issues. Commercially available computer platforms can reach animation rate in the order of tens of frames per second, depending on image size and score calculation complexity [20]. Although usually animation rate is 25 frames/s, actual rate must be matched with information processing capabilities of human observer. Otherwise, problems such as temporal summation and visual masking may arise. Both effects occur if the frame rate is too high, when details on adjacent maps interfere creating false percepts.

The most important computational issues for real-time visualization are complexity of score calculations, image size and animation rate. The careful design of our system provides full advantage of a multiprocessing distributed environment and real-time visualization [20].

4.2. Sonification

In addition to visualization, sonification is a second important presentation modality. Therefore we supported sonification in our environment. Relationship between visualization and sonification is itself a complex design problem, due to the nature of the cognitive information processing. Efficiency of sonification, as acoustic presentation modality, depends on other presentation modalities. The most important advantages of acoustic data presentation are [14]:

– faster processing than visual presentation;
– easier to focus and localize attention in space (appropriate for sound alarms);
– good temporal resolution (almost an order of magnitude better than visual);
– additional information channel, releasing visual sense for other tasks;
– possibility to present multiple data streams.

Disadvantages of acoustic rendering are:
– difficult perception of precise quantities and absolute values;
– limited spatial resolution;
– some sound parameters are not independent (pitch depends on loudness);
– interference with other sound sources (like speech);
– absence of persistence;
– dependent on individual user perception;

It could be seen that some characteristics of visual and acoustic perception are complementary. Therefore, sonification naturally extends visualization. The system must provide the ability to extract the relevant diagnostic information features. The most important sound characteristics affected by sonification are:
– *Pitch* is the subjective perception of frequency. For pure tones it is basic frequency, and for sounds it is determined by the mean of all frequencies weighted by intensity.
– *Timbre* is characteristic of instrument generating sounds that distinguishes it from other sounds of the same pitch and volume. The same tone played on different instruments will be perceived differently. It could be used to represent multiple data streams using different instruments.
– *Loudness* or subjective volume is proportional to physical sound intensity.
– *Location* of sound source may represent information spatially. Simple presentation modality may use *Balance* of stereo sound to convey information.

Early sonification applications have been mostly using so-called “orchestra paradigm”, where every data stream has assigned its instrument (flute, violin, etc.). Notes of different pitch then represent data values. The main advantage of this approach is the possibility to apply standard MIDI support, using system application programming interface (API). Unfortunately, this proposed approach often leads itself to cacophony of dissonant sounds.

An audio channel could be also used as feedback for positional control, which could be a significant aid for surgeons in the operating room. Just as musicians use aural feedback to position their hands, surgeons could position instruments according to a pre-planned trajectory, pre-placed tags or cues, or anatomical models. In a DARPA financed project CASI develops a training surgical simulator. Multiple parallel voices provide independent channels of positional information, used as a feedback during simulation or operation [23].

Sonification of EEG sequences has been applied previously to detect short-time synchronization during cognitive events and perception [18]. Each electrode is assigned a different MIDI instrument, and EEG synchronization is perceived as synchronous play during data sonification. We applied sonification as a modulation of a natural sound pattern in addition to visualization to reduce user information overload.

5. Multimodal viewer – *mmViewer*

The progress and availability of multimedia and virtual reality (VR) technology has made possible perceptual data presentation [1,3,8,9]. Techniques developed in virtual reality facilitate multiple data stream presentation and navigation through huge data sets. New immersive environments are particularly appropriate to improve insight into complex biomedical phenomena, which are naturally multidimensional. In an extension to visualization, which gives predominantly spatial distribution, acoustic rendering may improve temporal cues.

Our first visualization prototype was developed in Visual C++ for Windows 95/NT operating system [19]. The environment was developed to test the user interface and the most important perceptual features of visualization like animation control and speed, evaluation of scores, color mapping (look up tables), background properties, scene lighting, and model evaluation.

The second version was developed for a telemedical environment. We decided to base our VMDs on the virtual reality modeling language (VRML). The VRML is a simple language for describing 3D shapes and an interactive environment [7,22]. VRML is also intended to be universal interchange format for integrated 3D graphics and multimedia. VRML browsers, as well as authoring tools for the creation of VRML files, are widely available for many different platforms.

Therefore we have chosen VRML as our widely accepted platform for internet based information systems. In our system a VRML world is controlled by Java applets.

We developed the multimodal viewer *mmViewer* as a general-purpose environment for EEG analysis. The brain electrical activity is represented using animated topographic maps projected onto a 3D head model. Visualization could be synchronized with data sonification of the EEG data. Sonification is implemented by modulation of natural sound patterns to reflect certain features of processed data, and create pleasant acoustic environment. This feature is particularly important for prolonged system use.

5.1. System organization

The system consists of three parallel execution threads: *data acquisition*, *data processing*, and *data presentation*, which could be executed in parallel on different processors. Even in a single processor system, data acquisition is usually supervised by an intelligent controller on the A/D board, score calculation could be performed by an add-on DSP processor, while the graphics coprocessor can handle visualization tasks.

The EEG data could be fed either on-line from the A/D converter board or off-line from the archive file. We implemented the input filter for the EEG data format generated by *RHYTHM 8.0* (Stellate Systems), and now we are implementing standard ASTM EEG data format (see footnote 1). The VRML based *mmViewer* is developed for distributed web based information systems. The only requirement on the target machine is that the web browser will support VRML. The user interface of mmViewer is shown in Fig. 3. The basic system architecture is presented in Fig. 5.

Each execution thread is represented by a separate block in Fig. 5, while *user control block* represents central logical control of the system. The data acquisition block abstracts input data whether they come from input sensors or from a disk file to a temporal coherent data stream. The EEG data chunks are passed from the data acquisition to the *data source script* in the data processing block. The *data source script* routes the data to the VRML adapter block. The VRML adapter block is divided into the *visualization script* and the *sonification script*. The *visualization script* handles transformation of scores to visual presentation data, whilst the *sonification script* handles transformation to audio presentation data. The mapping process is under control of the *mapping script*. The mapping parameters are set through the user controls: *data source control*, *clock control*, *visualization control*, *sonification control* and *animation control* in *user control* block. These commands are routed through the mapping script to the appropriate adapter script. The visual and audio presentation is provided by corresponding parts of the standard VRML viewer. The head model is given through the `IndexedFaceSet` node where the mapping is accomplished through the changing vertex colors. The visualization implementation issues could be found in [20], here we will discuss only the sonification issues.

The VRML specification allows for the creation of virtual worlds with spatialized, 3D localized audio sources to achieve the sense of immersion and realism in a virtual environment. Perception of the sound source position is implemented using head-related transfer function (HRTF) algorithms [1,22]. Sonification is supported by the standard VRML nodes *Sound* and *AudioClip* [22]. The sound pattern is stored in the predefined audio file, and then modulated during animation. The Sound node specifies the spatial presentation of a sound source in a VRML scene as follows:

```
Sound{
exposedField  SFVec3f  direction  0 0 1  # (—,)
exposedField  SFFloat  intensity  1  # [0,1]
exposedField  SFVec3f  location  0 0 0  # (—,)
exposedField  SFFloat  maxBack  10  # [0,)
exposedField  SFFloat  maxFront  10  # [0,)
exposedField  SFFloat  minBack  1  # [0,)
exposedField  SFFloat  minFront  1  # [0,)
exposedField  SFFloat  priority  0  # [0,1]
exposedField  SFNode  source  NULL
field  SFBool  spatialize  TRUE
}
```

The sound is located at a point in the local coordinate system and emits the sound in an elliptical pattern. Two ellipsoids are defined with *minFront*, *minBack*, *maxFront*, and *maxBack* parameters. The ellipsoids are oriented in a direction specified by the *direction* field. The shape of the ellipsoids may be modified to provide more or less directional focus from the location of the sound.

The *source* field specifies the sound source for the Sound node. If the source field is not specified, the Sound node will not emit audio. The source field shall

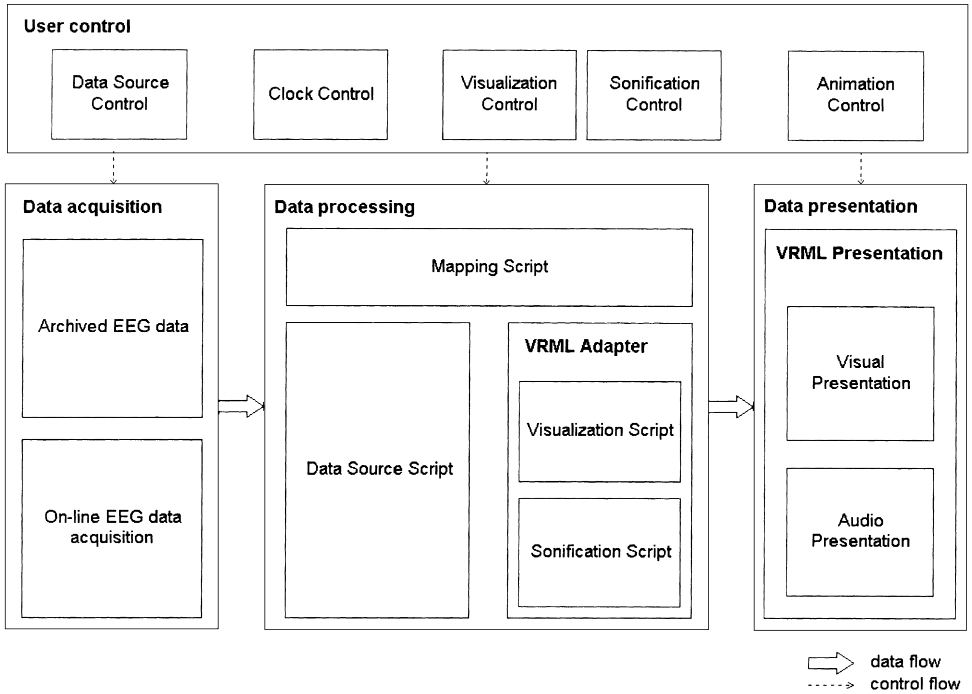

Fig. 5. *mmViewer* application architecture.

specify either an *AudioClip* node or a *MovieTexture* node.

The *intensity* field adjusts the loudness of the sound emitted by the Sound node. The *intensity* field has a value that ranges from 0.0 to 1.0 and specifies a factor, which shall be used to scale the normalized sample data of the sound source during playback. The *priority* field provides a hint for the browser to choose which sounds to play when there are more active Sound nodes than can be played at once due to either limited system resources or system load. The *location* field determines the location of the sound emitter in the local coordinate system.

6. Lessons learned

We were able to perceive that new generation of programming environments significantly reduce implementation efforts, providing support for the most frequently used functions. As an example, there is no need to implement means for viewpoint manipulation, as it is already supported directly by VRML viewer.

Principally, there are two possible ways of using sound in multimodal data presentations. The simplest one is signaling of state transitions or indication of certain states, which is often implemented as sound alarms, even on PC. The second one is acoustic rendering, or presentation of current values in data stream. Additional modes of presentation may be employed either as redundant mode of presentation emphasizing certain data features or to introduce new data channels. Redundant presentation creates artificial synesthetic perception of the observed phenomena [5]. Artificial synesthesia (*syn*=together, and *aisthesis*=perception in Greek) generate sensory joining in which the real information of one sense is accompanied by a perception in another sense. Introducing additional channels one should be careful to avoid information overloading.

Unfortunately, there are no obvious design solutions for multimodal presentations. It is very hard to find the most appropriate paradigm, or sound parameter mapping, for a given application. Therefore it is advisable to evaluate different visualization and sonification methods and find out perceptually most admissible presentation. Moreover, the creation of user-specific templates is highly advisable, as perception of audio–visual patterns is personal.

The selection of scores for multimodal presentation is another delicate issue relying on human perception. The score selected for acoustic rendering may be used either as a new information channel (sonification of symmetry in addition to visualization of EEG power [10,11]) or redundant channel of visualized information [9].We believe that multisensory perception could improve insight into complex biomedical phenomena [12].

7. Conclusion

Although standardization is a key issue for wider acceptance of telemedical information systems, experiences have shown that implemented systems often remain proprietary. Developed systems are often expensive, and do not have enough input to allow seamless integration with an existing system. Our proposed VRML based environment requires only a standard web and VRML 2.0 browser, and therefore it is applicable both to stand-alone workstations and distributed telemedical applications. Available VMD tools allow not only flexible views on the same data sets, but a new design approach to medical equipment.

The proposed web based EEG analysis environment is still in its experimental phase, but we have received very good response from the physicians in experimental and clinical settings. Redundant multimodal presentation offers the possibility to choose presentation modality for a given data stream, or to emphasize temporal dimension for a selected stream. In our example, the sonification method proved valuable in the dynamic following of some parameters of brain electrical activity that would be hard to perceive otherwise.

Future development in our system will include real head models derived with MRI recordings. Then we will be able to functionally map brain activity onto anatomic regions.

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