# SCALABLE EARCONS: BRIDGING THE GAP BETWEEN INTERMITTENT AND CONTINUOUS AUDITORY DISPLAYS

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## ABSTRACT

The development of blood pressure earcons for patient monitoring is used to illustrate how data that varies from intermittent to continuous sampling can be integrated into a single auditory display design. A scalable-earcon structure that extends the concept of hierarchies of earcons is proposed for representing blood pressure information. This structure allows the earcon to be used to produce intermittent earcons or a continuous sonification of blood pressure measurements. The results of two blood pressure earcon studies indicate that people can use the earcon to elicit large amounts of information with few major errors.

## 1. INTRODUCTION

The need to convey information across modalities in mission critical monitoring environments such as patient monitoring is well recognized [1]. Until recently most auditory displays have been used to direct attention to visual information; often with very poor results [2, 3]. Auditory displays that focus on conveying information rather than directing attention have the potential to reduce workload and support vigilance tasks that are common across mission critical environments. Approaches including sonifications, auditory icons and earcons may offer solutions that could increase situation awareness while reducing workload in patient monitoring and similar mission critical environments [4].

This paper describes some of the issues and solutions involved in designing auditory displays for patient monitoring. In particular this work focuses on the design of scalable-earcons to convey patient blood pressure information. The domain of patient monitoring is used to illustrate how the problem of designing auditory displays for complex noisy environments can be overcome by focusing on the attention and semantic mapping of data to sound [4]. The scalable-earcons reported here are designed to bridge the gap between earcons and sonifications for data sources, such as blood pressure, that vary in their rate of change or period of measurement.

### 1.1. Sonification and Earcons

Sonifications and earcons can compliment visual output by increasing the amount of information communicated to the user or reducing the amount of information the user has to receive through the visual channel. Sonifications and earcons differ in the types of information that they are suited to convey.

Sonifications are continuous auditory displays that code data into perceived relationships in sound [5]. The continuous nature of sonifications allows for changes in the dimensions of sound to not only direct attention but to also convey meaningful information such as the magnitude and rate of change of the data represented by the sonification. The continuous nature of sonification implies a need for the data it represents to update in a timely and continuous manner.

Blattner et al., describes earcons as “nonverbal audio messages that are used in the computer/user interface to provide information to the user about some computer object, operation or interaction” [6]. Traditionally these have been produced as musical motifs where the user learns to associate the motif with an action or a function of a computer/user interface. Earcons have been used to present information that is hard to discern visually or not available on visual displays [7, 8].

The short intermittent nature of earcons makes them highly suitable for conveying discrete events. Brewster et al., have proposed hierarchies of earcons that can be strung together to produce short messages. The usefulness of earcons is limited by people’s ability to recognize each component of an earcon. Sanderson et al., found people have only a limited ability to discriminate earcons used for anaesthetic alarms [9]. Similar findings have been found for the identification of auditory alarms in nursing [10]. The ability of people to identify information from a large range of earcons may be limited especially in high information environments where the context of the earcons may not be obvious.

## 2. PATIENT MONITORING

For clinicians, patient monitoring is based upon their expectation of likely changes in the patient’s state and vigilance for unexpected changes. Clinicians rely on integrating several sources of physiological information in conjunction with their knowledge of the patient history to avoid adverse patient events. In the noisy environments of operating theatres, intensive care units, emergency rooms and ambulatory monitoring, clinicians will rarely be able to dedicate their full attention to patient monitoring due to the demand of other medical tasks.

### 2.1. The Patient Monitoring Environment

Patient monitoring environments including operating theatres, intensive care units, emergency rooms and ambulatory monitoring are often noisy places. The patient monitoring equipment in these environments varies from limited non-invasive monitoring to complex and invasive measures of a patient’s physiology. The majority of patient monitoring equipment used in these environments provides clinicians with information through visual displays. In general the visual displays are augmented with auditory alarms to help direct attention to changes in the patient’s state.

In ambulatory monitoring, whether in a vehicle or moving a patient on a bed, visual displays are virtually ineffective due to the physical ergonomics of the tasks. The activity of pushing a bed down a busy corridor or the cramped environment of an ambulance or helicopter means that visual displays are difficult to mount and view.

In operating theatres and intensive care units visual displays are easier to use; however, the introduction of new patient monitoring devices has been accompanied by an increase in the numbers of auditory alarms. Although the intention of the auditory alarms is to direct the attention of clinicians to significant changes in the patient’s state, several studies have indicated the potential danger of the increased numbers of non-discriminating alarms [10, 11]. Alarms may be improved by making them more discernable; however, there are limits to the number of alarms people can recognize [10]. There is a clearly identified need for better auditory displays to support patient monitoring.

The pulse oximeter—a sonification—is the one patient monitoring example of an auditory display that allows the information to be interpreted with regards to the situation. The variable tone pulse oximeter was the first sonification to convey physiological information in medical displays. The pulse oximeter sonification provides information about oxygen saturation at the extremities of the body and the patient’s heart rate. The rate of the auditory pulses conveys heart rate while the pitch of the pulse conveys percentage oxygen saturation. In the Australian Incident Monitoring Study, Webb et al., found the pulse oximeter was the most successful monitor at detecting adverse patient events [12].

### 2.2. New Patient Monitoring Auditory Displays

Several research groups have developed auditory displays for patient physiological data that go beyond pulse oximetry [4, 13, 14, 15]. Most of these approaches have developed sonifications to convey information beyond heart rate and oxygen saturation. However only Watson and Sanderson [4] have attempted to map patient physiological data to sound based on the availability of data.

Watson and Sanderson [4] included an attentional mapping phase and a semantic mapping phase in their ecological interface design of auditory patient monitoring displays. Their work looked at the information requirements of anesthetists, the temporal availability of physiological data and the potential sound dimension mappings available across sound streams. Watson and Sanderson’s initial work focused on the development of a respiratory sonification; however, they identified the need to represent a range of other physiological data including blood pressure [4]. This paper focuses on the development of the auditory display for blood pressure.

### 2.3. The Problem of Information Inconsistency

In environments like patient monitoring not all information is reliable and some information may be intermittent. Information sources, such as non-invasive blood pressure that can provide data as infrequently as every five minutes, could cause a sonification of a physiological parameter to be misinterpreted by clinicians. In cases where invasive blood pressure measures are used, blood pressure data may be updated every heartbeat.

Prior attempts to represent blood pressure in sound have used sonifications [14, 15]. The problem with such displays is that if the blood pressure is measured non-invasively then the sonification may actually misrepresent what is happening to the patient [2]. Continuous representation of non-invasive blood pressure would reduce clinicians’ situation awareness as clinicians may base hypotheses on blood pressure information that could be several minutes old.

In the case of non-invasive blood pressure monitoring sonification is inappropriate; however, earcons have the potential to convey a range of blood pressure states. In cases where blood pressure is monitored continuously the data maps better to sonifications. However developing a different display for non-invasive and invasive measures of blood pressure is likely to increase the workload demands of clinicians to recognize the two displays.

The desire to bridge the gap between sonification and earcons for blood pressure monitoring has led to the development of a flexible scalable-earcon that can provide both intermittent and continuous information about blood pressure. The scalable-earcon extends the hierarchies of earcons of Brewster et al., to include a variable pitch scale that indicates both systolic and diastolic blood pressure [6]. The scalable-earcons are designed to assist clinicians to recognize abnormal or unexpected states. The scalable-earcons are also designed to work with the existing pulse oximeter and the respiratory sonification developed by Watson and Sanderson [4].

## 3. SCALABLE-EARCON FOR BLOOD PRESSURE

People’s ability to recognize scalable ranges in any one sound dimension is severely limited without a reference sound [5]. To support peoples’ perception the scalable earcons use a combination of duration and frequency. The mapping of blood pressure measurements are represented on a nine-point scale although a smaller number of points could be used (Figure 1). The duration of the tone indicates high, normal and low levels, and sub-levels within each range indicated by the pitch of the scale.

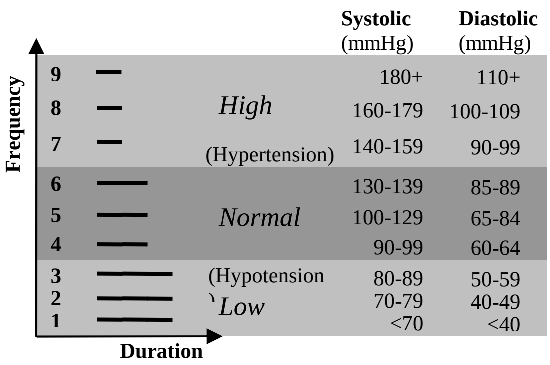


Figure 1. *The nine-point scale used as the basic building block for the blood pressure earcons.*

In the most basic form a single tone on the scale can be used to represent a range of blood pressure parameters, e.g. systolic, diastolic or mean blood pressure. Although the tone for the nine levels is the same for systolic, mean and diastolic blood pressure, the mapping to mmHg is different. The order of the tones is used to represent the type of measurement. In the experiments run to date, blood pressure has been represented as systolic followed by diastolic.

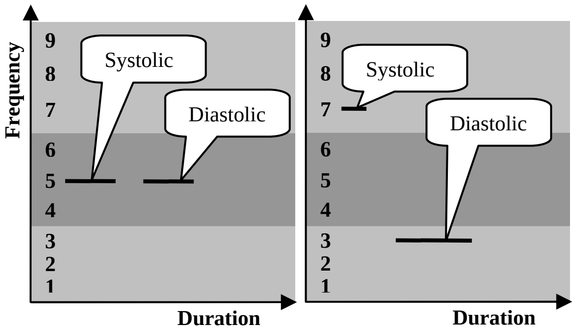


Figure 2. *The left figure shows a map of the frequency and duration for a normal systolic and diastolic blood pressure while the right figure shows an unusual blood pressure reading of a high systolic and low diastolic.*

The combination of two or more tones forms the basis of the blood pressure earcons (Figure 2). For example a systolic measurement followed by a diastolic measurement produces a two-toned earcon. Each tone is separated by a fixed duration based on high value duration of the tone. Changes in the duration of each tone affect the tempo of the earcon to form discreet sound messages in much the same way as Morse code does. For a two tone version of the earcon there are theoretically 81 possible sound messages. Not all 81 combinations are physiologically possible when representing systolic and diastolic blood pressure in the earcon as systolic blood pressure cannot be less than diastolic blood pressure.

### 3.1. Supporting Recognition of Trends

Clinicians not only require information about the current state of a patient's blood pressure but they are also interested in blood pressure trends. The basic blood pressure earcon can be expanded to add extra historical information. By preceding the current value of systolic and diastolic blood pressure with the previous earcon recent trends can become apparent. In the example in Figure 3 the change in tempo and frequency makes the increase in blood pressure immediately obvious.

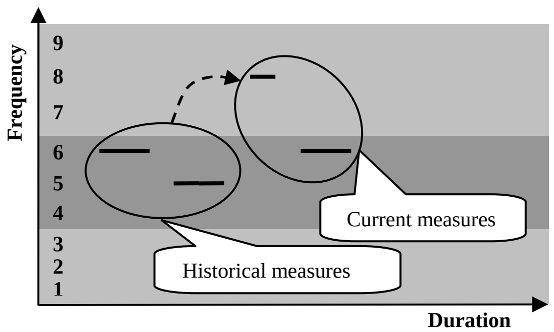


Figure 3. *An example of an earcon containing historical information for trend recognition.*

Historical information in the earcon would be of most value when blood pressure monitoring is infrequent. The increase in the number of tones used also increases the amount of information available for the listener to compare and therefore identify the exact levels of systolic and diastolic blood pressure.

The inclusion of an auditory beacon can also assist the listener to identify changes in blood pressure.

### 3.2. Improving Scale Recognition with Beacons

Reference beacons can be placed in the earcon to help listeners identify blood pressure changes. The beacon helps to form a pattern that makes deviations from normal immediately apparent (Figure 4). The beacon also assists with the comparison of both pitch and duration changes in rest of the earcon.

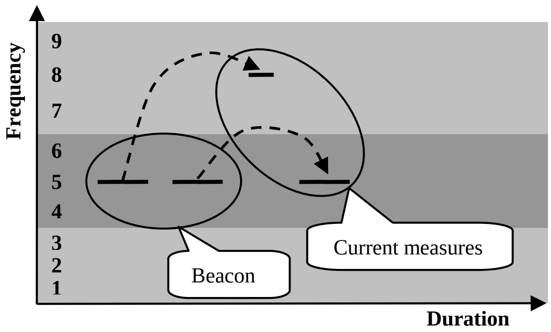


Figure 4. *An example of a reference beacon for the blood pressure earcons.*

If the time between earcons becomes long, beacons may also assist people to change their attention from other tasks. When a patient has a steady blood pressure that differs from normal, a dynamic beacon can be set to help identify changes in the patient's blood pressure. The dynamic beacon could be set by capturing the patient's current steady state and using that as the reference for change. The placement of a beacon prior to the earcon produces an effective reference point which will be discussed in the findings to date section.

### 3.3. Supporting Continuous Blood Pressure Monitoring

The design of the basic building block allows the earcon to run together to form a sonification of blood pressure. By ensuring a gap between earcons that is at least as long as the low blood pressure duration, distinguishing systolic from diastolic measures becomes apparent (Figure 4). Systolic and diastolic blood pressure information could be updated through the sonified earcon every second; however, such a rate is clinically unwarranted. A rate of five to ten times a minute is likely to give adequate warning to clinicians about abnormal patient events. The slower rate of update also reduces the potential for interference between the pulse oximeter and the blood pressure information.

## 4. FINDINGS TO DATE

Two studies were conducted to examine peoples' ability to interpret the earcons. The first study is reported by Watson and Gill [16]. In both studies, experiments each of 24 non-medical participants were used to examine people's perceptual ability to monitor historical and current information from the blood pressure earcons. The initial work examined three conditions, the first provided information about the patient's 'current' systolic and diastolic blood pressure. The second earcon was presented with a beacon before the systolic and diastolic measurements. The third earcon used the beacon followed by the previous measurements of blood pressure and finally information about the current systolic and diastolic blood pressure measurements. In the second study the beacon was replaced by an alert to test if the improvement found in the beacon conditions was due to the switching of attention from the distractor task or people using the beacon as a pitch and duration reference.

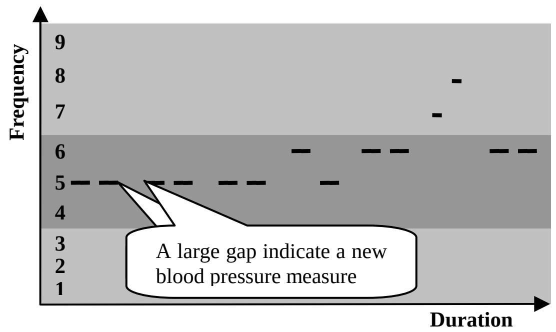


Figure 4. *An example of a continuous version of the blood pressure earcons.*

Participants received 45 minutes training with the earcon prior to conducting the evaluation. Participants monitored a simulated patient's blood pressure every two minutes while conducting an attention demanding arithmetic distractor task. They listened to pulse oximetry and a respiratory sonification during the experiment as potential sources of masking.

The results of the experiments indicated that participants performed at a higher level of accuracy in all conditions when compared to the results of alarm studies [9, 10]. When participant's indicated a wrong result for blood pressure measurement the modal error was 1 away from the correct answer on the nine-point scale. When comparing the results of the two experiments the beacon improved participants' performance. In both experiments the inclusion of historical information in the earcons produced a trade-off between participants accuracy on current systolic and diastolic values with historical systolic and diastolic values.

## 5. CONCLUSION

This work extends the hierarchies of earcons by Brewster et al., to allow a greater number of earcons to be recognized through a scalable rule structure [6]. The use of scalable-earcons is limited to displays where a regular scale can be produced for each parameter represented in the earcon. The use of a combination of pitch and duration for a nine-point scale produced highly accurate results with a group of participants with minimal training; however, it may be difficult to go beyond nine points given people's limited ability to accurately identify pitch without extensive training [5].

To develop auditory patient monitoring displays that go beyond pulse oximetry requires detailed consideration of the limits of both the data to be represented and the psychoacoustic constraints of the listener. Further evaluation of the blood pressure scalable-earcons is needed in a full scale simulator and a clinical setting is required to examine if clinicians can integrate the information in the earcon with visual information and other auditory displays.

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