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Continuous sonification enhances adequacy of interactions in peripheral process monitoring

Tobias Hildebrandt [a,*], Thomas Hermann [b], Stefanie Rinderle-Ma [a]

[a] Workflow Systems and Technology, Faculty of Computer Science, University of Vienna, Waehringerstr. 29, 1090 Vienna, Austria
[b] Ambient Intelligence Group, Cluster of Excellence - Cognitive Interaction Technology (CITEC), Bielefeld University, Germany

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ABSTRACT

As many users who are charged with process monitoring need to focus mainly on other work while performing monitoring as a secondary task, monitoring systems that purely rely on visual means are often not well suited for this purpose. Sonification, the presentation of data as (non-speech) sound, has proven in several studies that it can help in guiding the user's attention, especially in scenarios where process monitoring is performed in parallel with a different, main task. However, there are several aspects that have not been investigated in this area so far, for example if a continuous soundscape can guide the user's attention better than one that is based on auditory cues. We have developed a system that allows reproducible research to answer such questions. In this system, the participants' performance both for the main task (simulated by simple arithmetic problems) and for the secondary task (a simulation of a production process) can be measured in a more fine-grained manner than has been the case for existing research in this field. In a within-subject study ($n=18$), we compared three monitoring conditions – visual only, visual + auditory alerts and a condition combining the visual mode with continuous sonification of process events based on a forest soundscape. Participants showed significantly higher process monitoring performances in the continuous sonification condition, compared to the other two modes. The performance in the main task was at the same time not significantly affected by the continuous sonification.

1. Introduction

Business processes such as in manufacturing and logistics or in administration, but also technical processes like in robotics, are becoming increasingly complex while they are at the same time more and more automated, computerized and monitored in real-time (Malone et al., 2003).

This is true for processes in many domains, but especially for industrial productions, where a delayed delivery of raw materials can lead to a standstill in production and thus high loss of profit. On the one hand the increasing amount of data offer an enormous potential to better monitor and control processes. On the other hand it puts increasing pressure on monitoring personnel who need to observe processes.

The status quo in large-scale process monitoring is heavily focused on control centers where users observe production on multiple screens, using both video features as well as schematic overviews of process and machines/facilities, charts/graphs, textual descriptions and alerts (Sauer, 2004).

Especially in smaller- and medium-sized production companies, there are often no dedicated personnel charged with full-time monitoring, but instead engineers and supervisors need to primarily perform other tasks, yet monitor the process' status at the same time. However, especially in such peripheral or *serendipitous-peripheral monitoring* scenarios where the attention is focused on a primary task and other information is monitored indirectly at the same time, visual means are not well suited, as pointed out by Vickers (2011).

Meanwhile, maintenance experts have been using the auditory sense to identify or anticipate possible machine problems, a technique referred to as vibration analysis, for a long time. Crucial vibration properties are amplitude, frequency, phase and modulation (Renwick and Babson, 1985). Therefore, traditional production monitoring is still considered to be a holistic approach, covering the visual, auditory and even olfactory sense, even though automation has enhanced *manual* vibration analysis in the recent years (Hildebrandt et al., 2014b).

In modern production settings, sound is typically only used as a means to convey warnings and alerts, e.g., to convey an alarm situation when a machine broke down or a predefined threshold had been exceeded (Siemens, 2007). In a production scenario, this

* Corresponding author.
E-mail address: Tobias.Hildebrandt@univie.ac.at (T. Hildebrandt).

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could for instance be the case when the stock level of a resource has dropped below a critical level, or when a temperature sensor of a machine measures a critical temperature, indicating imminent machine failure (SAP SE, 2015).

However, this type of auditory display has several drawbacks: on the one hand, if rules that define alert triggering thresholds are defined too *conservative*, i.e., requiring strong evidence before issuing positive classifications, potentially critical situations such as machine failures might occur without issuing an alert. On the other hand, if the values are defined too *liberal*, i.e. risking high false positive rates, the resulting flood of (in many cases unnecessary) alerts and alarms might lead to an information overload of the user, or to the situation that the user stops to take the alerts as serious as they are. Furthermore, in many scenarios engineers are not able to define all states and values that might lead to a critical situation beforehand. Levels and values that might constitute a critical state are often complex to decide, as e.g., the question if a specific parameter value constitutes a critical situation or not often depends on the context, given by various other parameters. But even if all possibly critical situations are covered by alerts and alarms, in most cases operators might prefer to be informed even *before* a situation might become critical, thus enabling them to *anticipate*, *intervene* and *avoid* the problem. A constant awareness of states and values through an *auditory ambient information system* might enable such an anticipation of critical situations. Thus, we suggest to use the mentioned tradition of auditory monitoring as a leverage effect by supplementing state-of-the-art visual process monitoring with techniques from sonification.

Sonification is the systematic, reproducible and thus scientific method for representing data as (mostly non-speech) sound in an auditory display (Hermann, 2008). Well-known examples of sonifications are the Geiger counter for displaying radioactive radiation, or the auditory parking aid which conveys the distance to the vehicle or obstacle behind as pulse rate of a beep sound. Beyond these very basic and simple types, sonification researchers have developed a plethora of approaches to represent more complex data such as multivariate time series (e.g. EEG and ECG), or spatio-temporal data (e.g. images and well logs), and also general high-dimensional data distributions.

Sonification has several key advantages that makes it suitable especially for the application area of real-time process monitoring, like our ability to process audio faster than visuals or the fact that we easily habituate to static sound sources, yet that we are at the same time very sensitive to changes (Vickers, 2011).

For these reasons sonification promises a solution to the aforementioned challenges of state-of-the art process monitoring. However, there are several open questions when it comes to supporting users in monitoring as a secondary task that concern the sonification design and as well as how different types of sound-enhanced process monitoring affect attention and concentration in main- and secondary task, which we tackled with this paper. Our main research goals were (a) to find out if a continuous, soundscape-based sonification of individual production steps can support users better in monitoring as a secondary task than a purely-visual solution, or one that is based on auditory alerts. Other open research questions were (b) to what extent the three different conditions distract users from their main task, (c) how users rate the three different conditions concerning relevant aspects such as pleasingness, helpfulnesses, intrusiveness or exhaustiveness. Answering those research questions poses several challenges, such as simulating the potential users' main- and secondary task in such a way, that they are both cognitively demanding and thus binding the undivided attention, while at the same time allowing for an easy and reliable measurement of task performance in a fine-grained manner. As there are no standardized environments that fit these requirements, we have developed the SoProMon system (Sonification for Process monitoring), that is a hard-/software system for reproducible research in sonification for peripheral monitoring, particularly for the investigation of attention allocation in dual-task-settings. The system has already been presented in Hildebrandt et al. (2014a), and consists primarily of a main task console to bind the user's attention by presenting simple arithmetic problems and a simulated production process that requires different types of user interactions (see Section 4). Based on the SoProMon system, we conducted an extensive experiment in a within-subject design (n=18), whose results contribute to answering the mentioned open research questions, and thus to advancing research in this area (see Section 2) in the following ways:

- To our best knowledge no quantitative experiments using soundscapes in dual-task settings have been conducted so far. The experiment that we conducted featured a sonification based on a forest soundscape design (see Hildebrandt et al., 2014a) to enable long-term listening without fatigue.
- Sonification designs in previously conducted experiments for peripheral process monitoring either base on auditory cues, or on continuous sonifications. The experiment described in this paper compares three conditions: visual only, visual + auditory cues and visual + continuous soundscape sonification.
- Furthermore, dual-task experiments that have been conducted in this area measure the performance in both tasks typically using either binary correctness measures and/or response times. In our experiment, we employ a more fine-grained performance measurement in which for each user interaction a continuous score is assigned that either measures correctness (main task) or adequacy (secondary, process monitoring task).
- In most quantitative experiments, the user's opinion on e.g. the different conditions and his/her understanding of those is not gathered, or if it is, not in a very fine-grained way. For the experiment we developed an extensive questionnaire that features a pre experiment-, three postcondition- and one post-experiment part.

As industrial production is an area, in which it is especially crucial to monitor processes in real-time and that can probably be intuitively understood also by domain novices, the secondary task of this experiment is based on a simulated production processes. However, as the experiment design aimed at quite fundamental questions of attention allocation, the results should be generic enough to be transferable to monitoring scenarios in other domains as well.[1] The details on the current state-of-the-art concerning research in sonification for (peripheral) process monitoring as well as on the open research issues that we tried to tackle with the experiment can be found in Section 2. The hypotheses derived from the literature which we tried to tackle with the experiment are described in Section 3, followed by an introduction into the SoProMon system (Section 4) and the methodology of our experiment (Section 5). Experimental results will be presented in Section 6 and discussed in Section 7, followed by overall conclusive considerations.

2. Related work

There is a substantial amount of research concerning applications of auditory process monitoring, spanning various areas such as industrial production processes, program execution or web

[1] Preliminary results from selected questionnaire items have been presented in an extended abstract (Hermann et al., 2015).