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Categorization of seismic sources by auditory display: A blind test ☆

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ABSTRACT

Recordings of the Earth's surface oscillation as a function of time (seismograms) can be sonified by compressing time so that most of the signal's frequency spectrum falls in the audible range. The pattern-recognition capabilities of the human auditory system can then be applied to the auditory analysis of seismic data. In this experiment, we sonify a set of seismograms associated with a magnitude-5.6 Oklahoma earthquake recorded at 17 broadband stations within a radius of ~300 km from the epicenter, and a group of volunteers listen to our sonified seismic data set via headphones. Most of the subjects have never heard a sonified seismogram before. Given the lack of studies on this subject, we prefer to make no preliminary hypotheses on the categorization criteria employed by the listeners: we follow the "free categorization" approach, asking listeners to simply group sounds that they perceive as "similar." We find that listeners tend to group together sonified seismograms sharing one or more underlying physical parameters, including source–receiver distance, source–receiver azimuth, and, possibly, crustal structure between source and receiver and/or at the receiver. This suggests that, if trained to do so, human listeners can recognize subtle features in sonified seismic signals. It remains to be determined whether auditory analysis can complement or lead to improvements upon the standard visual and computational approaches in specific tasks of geophysical interest.

1. Introduction

Seismologist Hugo Benioff first implemented a technique to accelerate seismograms to the range of audible frequency, compiling a set of sonified seismograms that was commercially released in 1953 in the form of an LP album (Karney, 2015). It was then suggested that earthquakes could be discriminated from man-made explosions by simply listening to the associated sonified time series, exploiting the high resolving power of the human auditory system (Speeth, 1961; Frantti and Levereault, 1965). This proposed approach was never put into practice: with the advent of digital seismology in the 1970s, automated software could accurately estimate hypocenter locations and source mechanisms by processing large seismic databases (Dziewonski et al., 1981; Ekström et al., 2012).

In principle, auditory analysis could contribute to current research topics in seismology. Humans have a powerful facility to understand physical characteristics of a process through sound, such as the mechanical nature of an impact. We assess the materials involved (metal, wood, glass, plastic) and the magnitude of forces involved. The question for this study is: Can we use this ability to characterize physical aspects of an unknown process, such as an earthquake? And for future work, can this ability be trained? How do we build this capacity, and then integrate it into practical analysis?

Research on the nature of earthquake rupture could also benefit from auditory display. As an example, the *Source Inversion Validation initiative* (Mai et al., 2012) was a blind test of multiple methods of dynamic and kinematic inversion of seismic observations (Ruiz and Madariaga, 2013) to produce a map of an earthquake rupture (the displacement along a fault during a single seismic event). Results show that the current signal processing techniques do not lead to robust models of earthquake rupture (the displacement along fault during a single seismic event). It is worthwhile to explore whether auditory analysis can help discriminating signals originating from different types of earthquake rupture. Study of human auditory analysis could lead to improvements in the signal processing algorithms for analysis of seismograms. Such improvements could also aid methods of engineering and real time control of fluid pumping in

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reservoirs, for hydrocarbons extraction, carbon sequestration and geothermal energy systems. Other potential applications are discussed at the end of the paper.

Over the years, a small community of researchers has continued to sonify seismic data for a number of (often educational or artistic) applications (Steinbrugge, 1974; Hayward, 1994; Dombois, 2001, 2002; Meier and Saranti, 2008). However, even though interest around sonification seems now to be growing in seismology (Hermann et al., 2011; Dombois and Eckel, 2011; Michael, 2011; Kilb et al., 2012; Peng et al., 2012; Holtzman et al., 2014) as well as other disciplines (Cowen, 2015; Worrall, 2009), the capability of the human auditory system (Benade, 1990; Hartmann, 1999; Roederer, 2008) to recognize patterns in seismic sound has not been studied quantitatively. No study so far has dealt with the discrimination of sonified seismic signals by human listeners, or, more generally, with our strategies (if any) of hearing, listening to, recognize, organize, or process such signals. The unique experiment of (Speeth, 1961) explored the human ability to distinguish sonified records of explosions vs. seismic events: a relatively simple, and very specific task.

In the experiment presented here, we proposed the listeners to categorize freely a set of sonified seismic data. As explained in Section 3, no information on the nature of such data (other than the fact that they were recordings of earthquakes) was provided, and the only criterion for grouping the data was their perceived “similarity.” Since all signals were generated by the same seismic event, we expected listeners to discriminate based on source–receiver distance, source–receiver azimuth and/or crustal structure between the source and the receiver. In the free-categorization approach, however, no specific hypothesis is tested directly, and it is *a priori* possible for a listener to group data according to a valid criterion not anticipated by the researchers.

Individual audio signals used in this study are produced by simple time-compression of seismic signals and are administered to listeners monophonically (the same signal is played through the two channels of the headphones, in phase) one at a time. This deliberately simple study is a first step towards the auditory analysis of spatialized seismic data; preliminary experiments in the spatialization of seismic sounds are described by Holtzman et al. (2014).

2. Seismic signals

2.1. Brief geology and seismology overview

Our newly compiled database of sonified seismograms is based on records of a recent sequence of 40 Oklahoma earthquakes of magnitude ranging between 3 and 5, recorded by 17 stations at local epicentral distances (Fig. 1). All data were collected in the framework of the USArray experiment (Kerr, 2013) and were recorded by broadband seismic sensors. In order to achieve the best possible signal quality, we limited ourselves to the largest event (magnitude 5.6, November 6, 2011) in the sequence (Keranen et al., 2014). Throughout this study, only vertical-component records are used. The 17 stations contributing to our database are located at latitudes 34°N to 37°N and longitudes 94°W to 97°W. The earthquakes are demonstrably caused by injection of large volumes of wastewater from “hydrofracturing” (Keranen et al., 2014; van der Elst et al., 2013), for long-term storage, in formations that contained oil that was previously extracted. The high fluid pressures trigger earthquakes, particularly when the fluid accumulates on old, inactive faults, reactivating them (Fig. 2). These events have been selected for the large quantity and high quality of available data recorded locally at diverse azimuths and distances, for the reliability of hypocenter locations, and, after a preliminary auditory analysis, for the perceived quality of sonified signals.

The character of observed waveforms propagating through the region of interest is related to the properties of the underlying crust (Udías, 1999; Aki and Richards, 2002). These are best summarized by surface-wave phase velocities at different periods, each sampling a different depth range as illustrated, *e.g.*, by Fry et al. (2010). The most recent and most complete surface-wave velocity model of North-America is that of Ekström (2013). We show in Fig. 3 a few examples

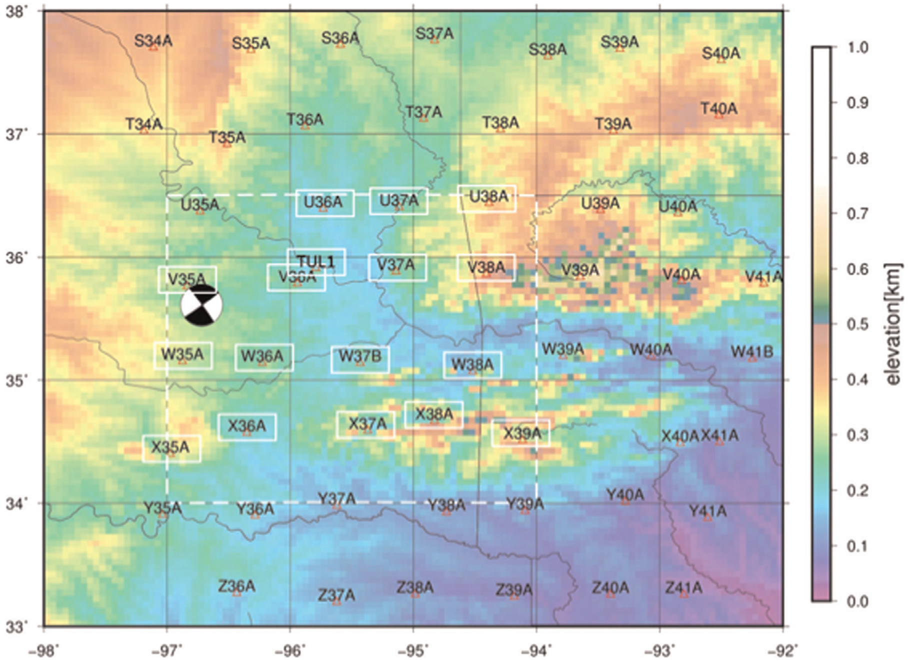

Fig. 1. Topography of the study area. The CMT focal mechanism (Dziewonski et al., 1981; Ekström et al., 2012) of the November 6, 2011, magnitude-5.6 event is plotted at the CMT epicenter location (compressional quadrants are shaded), suggesting a strike-slip fault with roughly SW-NE or SE-NW strike. Red triangles denote available seismic stations, whose names are specified. Different colors represent different elevations of the Earth's surface with respect to sea level. The dashed white line denotes the boundaries of our area of study. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

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