0 INTRODUCTION

Traditionally in audio signal processing the phase spectrum of an audio signal is assumed not to play a significant role in general. The claim that the ear is "phase deaf" was already suggested by Ohm [1], and Helmholtz came to the same conclusion in his tests [2]. This assumption about the auditory system is often exploited in audio signal processing, such as in audio coding [3,4,5,6]. The phase spectrum of an audio signal is often modified by the processing, for example, due to downmixing, quantization, and, especially, decorrelation. Decorrelation techniques, which basically scramble the phase spectrum, are needed in these methods for obtaining incoherent signal components.

Hence, these techniques assume that humans do not perceive modifications in the phase spectrum. As listening tests show, this assumption holds well for most of the signals [4,6,7]. However, recently it has been noticed that with certain signals, such as applause-type [8,9] and anechoic speech signals [10], humans are sensitive to changes in the phase spectrum. In order to obtain the optimal perceptual quality, a different kind of processing is needed with these "phase-sensitive" signals. Thus, finding an objective measure that predicts how perceivable the phase modifications are with any given signal would be useful. The aim of this work is to develop such a measure.

Human perception of the phase spectrum has been studied after the work of Ohm and Helmholtz, and several studies clearly show that humans are not phase deaf [11,12, 13,14]. For example, a cosine-phase harmonic complex signal, in which all of the components start simultaneously at their maximum amplitude, is perceived differently than a random-phase signal, in which the starting phase of each component is random [14]. In addition, even small changes in the phase spectrum within auditory frequency bands have been observed to yield perceivable differences, whereas changes between the bands are reported not to be perceivable [15], or at least large changes in the phase are needed in order to have a perceivable difference [14]. Furthermore, changing the phase of even a single component of a harmonic complex signal can be perceivable [16]. The perception of the phase spectrum has also been studied in relation to many topics, such as concert hall acoustics [17,18,19], pitch perception [20], vowel identification [21], masking [22], speech processing [23], and binaural rendering [24].

This article starts by reviewing the basics of human hearing and previous studies about phase perception. Based on these, a set of formal listening tests were arranged using synthetic harmonic complex signals in order to obtain more detailed knowledge about the properties of phase perception. Differences in the phase spectrum are known to affect perception, but the significance of these differences is not completely clear. In experiments 1 and 2, the perceptual significance of phase distortion was compared to magnitude distortion. Furthermore, it is not known if the differences in perception due to the phase modifications are global or local in frequency. In order to study this, phase modifications were applied to different bandwidths in experiment 3. Experiment 4 studied how wide in frequency is the perceptual effect of changing the phase at a certain frequency. In addition, the phase spectrum has been seen to affect the timbre. In experiment 5, it is shown that the loudness of the