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Research paper

Auditory velocity discrimination in the horizontal plane at very high velocities

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ABSTRACT

We determined velocity discrimination thresholds and Weber fractions for sounds revolving around the listener at very high velocities. Sounds used were a broadband white noise and two harmonic sounds with fundamental frequencies of 330 Hz and 1760 Hz. Experiment 1 used velocities ranging between 288°/s and 720°/s in an acoustically treated room and Experiment 2 used velocities between 288°/s and 576°/s in a highly reverberant hall. A third experiment addressed potential confounds in the first two experiments. The results show that people can reliably discriminate velocity at very high velocities and that both thresholds and Weber fractions decrease as velocity increases. These results violate Weber's law but are consistent with the empirical trend observed in the literature. While thresholds for the noise and 330 Hz harmonic stimulus were similar, those for the 1760 Hz harmonic stimulus were substantially higher. There were no reliable differences in velocity discrimination between the two acoustical environments, suggesting that auditory motion perception at high velocities is robust against the effects of reverberation.

1. Introduction

One of the major challenges to the auditory system in everyday listening is to track moving sound sources to predict their future path (e.g., an approaching car, a buzzing mosquito). However, our understanding of the perceptual (and physiological) mechanisms involved in the processing of auditory motion lags behind that for static sound localization. Most work on auditory motion perception is based on the Minimum Audible Movement Angle; MAMA), which is closely related to the Minimum Audible Angle (MAA; Mills, 1958) for static sound localization. In a typical MAMA experiment, participants are presented with a stimulus that is moving either to the left or to the right and are asked to discriminate the direction of movement. Studies have established that the MAMA can be as low as 2–5° for movement in the horizontal plane, provided the stimulus is wideband or contains low-frequency energy (e.g., Harris and Sergeant, 1971; Grantham, 1986). Saberi and Perrott (1990) found that in the vertical plane the MAMA can be as low as 6°. Still, little is known about the perception of velocity (Carlile and Best, 2002).

The aim of the present study is to contribute to empirical work on auditory velocity perception by examining two factors that have received scant attention in the literature. The first is auditory velocity perception at high velocities. As will be argued below, work on auditory motion perception and work on the 'sluggishness' of binaural hearing converge to suggest that people are capable of processing auditory motion at velocities that are at least one order of magnitude higher than the velocities that have been used in research on auditory velocity discrimination. Consequently, we do not have a full picture of velocity perception spanning the entire range of audible motion. The second aspect that has been underexplored is the effect of room reverberation. In what follows we discuss these facets in more detail and then introduce the aim of the current study.

1.1. Auditory velocity perception

Only a handful of studies have looked at the ability to discriminate the velocity of moving sounds. Waugh et al. (1979) asked

Abbreviations: ITD, interaural time difference; JND, just-noticeable difference; MAA, minimum audible angle; MAMA, minimum audible movement angle; VBAP, vector base amplitude panning; HS, harmonic sound; WN, white noise

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participants to judge the velocity of a moving stimulus in miles per hour. Although participants grossly overestimated actual speeds, they were nonetheless able to discriminate between velocities ranging from 15 to 360°/s.

Fig. 1a shows an overview of the results of psychophysical studies that measured discrimination thresholds, or just-noticeable differences (JNDs) for auditory velocity. JNDs were first measured by Altman and Viskov (1977) for velocities ranging between 14°/s and 140°/s. Carlile and Best (2002) measured discrimination thresholds using virtual sound sources spatialized using Head Related Transfer Functions. Grantham (1986) simulated sound movement through stereophonic panning. Whereas these studies used movement along the horizontal plane, Agaeva (2004) measured velocity discrimination thresholds in the vertical plane and found that discrimination thresholds were in the same range as, if not lower than, those in the horizontal plane. This seemingly better performance in the vertical plane is interesting given that horizontal localization is generally more acute than vertical localization (Grantham et al., 2003; Makous and Middlebrooks, 1990).

Fig. 1a shows a monotonic increase in JNDs with velocity. Such a trend appears to be in line with Weber's law (Gescheider, 1997), according to which the change in stimulus velocity that can just be discriminated (Δv) is a constant fraction (k), the Weber fraction, of the reference velocity (v): $\Delta v = kv$. However, the one study that

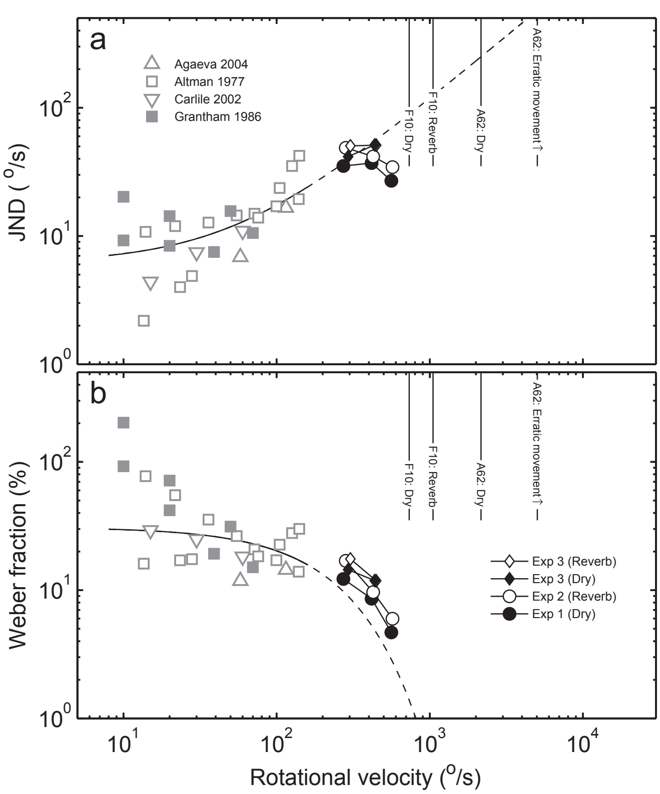

Fig. 1. Graphical summary of the literature on auditory motion discrimination in free field experiments. Only those studies in which the sound moved along an arc at a constant distant to the listener are included. (a) Just-noticeable differences (JNDs). The regression line is based on linear regressions using iteratively reweighted least squares with a bisquare weighting function, with the dotted parts showing the extrapolation. Note that the linear regression line appears curvilinear because both of the axes are logarithmic and the intercept of the line is non-zero. The vertical lines represent upper limits of rotational auditory motion perception found in previous studies (F10: Féron et al., 2010; A62: Aschoff., 1962). The lines marked with F10 correspond to the upper limits averaged across the various stimuli used in that study. (b) Weber fractions. The circles in both panels represent the present results averaged across stimuli. The regression line shows a fit of an exponential function (Gescheider, 1997).

explicitly reported Weber fractions (Altman and Viskov, 1977) revealed a clear exponentially *decreasing* trend; further this trend holds across all studies. Auditory velocity discrimination violates Weber's law.

The present work was motivated by two lines of research on the upper limits of auditory motion perception that strongly suggest that the binaural system is capable of processing velocities at least an order of magnitude larger than those considered in previous velocity discrimination studies (see the truncated vertical lines in Fig. 1). In studies of the sensitivity to dynamic interaural differences (Blauert, 1972; Grantham, 1982, 1984; Grantham and Wightman, 1978; Thompson and Dau, 2008), participants are asked to discriminate an unmodulated stimulus from a stimulus in which an interaural parameter (e.g., interaural time or intensity difference) is modulated at a rate, f_m. These modulations simulate the dynamics in interaural differences of a sound moving to and fro along a circular path. The modulated parameter has been interaural time difference (e.g., Blauert, 1972; Grantham and Wightman, 1978), interaural intensity difference (e.g., Blauert, 1972; Grantham, 1984; Thompson and Dau, 2008), and interaural correlation (e.g., Grantham, 1982).

Two main findings from these dynamic interaural differences studies are highlighted here. First, although the auditory system generally becomes less efficient at following the fluctuation as f_m increases, people are capable of discrimination at modulation frequencies up to 5 Hz (Grantham and Wightman, 1978), and in some cases as high as 50–100 Hz (Burns and Colburn, 1977; as cited in Grantham and Wightman, 1978). Second, thresholds depend on the spectral content of the stimulus. For instance, the binaural system is more efficient at following fluctuations in interaural correlation at low frequencies (0.5 kHz) than at high frequencies (2 and 4 kHz) (Grantham, 1982). The reverse seems to hold for fluctuations in interaural intensity differences; discrimination is better at high frequencies (1 and 4 kHz) than at low frequencies (0.5 kHz) (Grantham, 1984).

Free-field studies confirm that people can perceive auditory motion at very high speeds. Aschoff (1962) gradually increased or decreased the velocity of a white noise sound rotating around the listener at between 0 and 20 rotations per second. While at relatively slow velocities listeners reported that the noise was moving in a circle around them, as the velocity increased to 3.5–6 rot/s (i.e., ~1200–2200°/s), the noise was perceived to oscillate between the left and right sides. This left-right sensation was even more salient between 6 and 14 rot/s. Finally, above 14 rot/s (i.e., ~5000°/s) the sound movement took on an erratic nature and could no longer be localized. More recently, Féron et al. (2010) found that the "upper limit" of rotational auditory motion perception was around 3.3 rot/s (i.e., ~1200°/s), but depended on the spectral content of the stimulus; while a harmonic sound with a fundamental frequency of 330 Hz and a white noise produced similar upper limits, a harmonic sound with a fundamental frequency of 1760 Hz produced a significantly lower upper limit. In other words, motion perception was more robust for stimuli containing low-frequency energy than for stimuli containing only relatively high-frequency energy.

While high velocities remain largely underexplored in the scientific literature, they have garnered increased attention in music composition over the past 50 years with the emergence of electroacoustic and mixed music. The compositions of Stockhausen (1959) and Nunes (1998) exemplify the use of sounds moving at very high velocities for the purpose of musical expression.

1.2. Auditory motion perception in reverberant environments

Most research on auditory spatial perception, including auditory motion, has been conducted in (quasi-) anechoic environments. In