USING SPATIALIZED SOUND TO ENHANCE SELF-MOTION PERCEPTION IN VIRTUAL ENVIRONMENTS AND BEYOND: AUDITORY AND MULTI-MODAL CONTRIBUTIONS

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1 Introduction

Embodied self-motion illusions ("vection") have long fascinated both researchers and laypeople. With the increasing quality and affordability of immersive virtual reality (VR) and tele-operation/tele-robotics interfaces, there is also increasing interest in providing compelling sensations of self-motions to create more life-like and convincing experiences [4, 13, 21]. Whereas most research on self-motion perception focuses on visual and vestibular contributions, auditory input can also play a relevant role. Here, we will provide an overview of research indicating how spatialized sound (moving sound fields) can both induce self-motion illusions in blindfolded listeners and enhance self-motion illusions induced by other modalities.

2 Auditory vection

Although vection research has traditionally focused on self-motion illusions induced by moving visual cues, it has been known for more than a century that blindfolded stationary listeners can also experience illusory sensations of self-motion (auditory vection) when listening to moving sound sources [23, 24]. Visually-induced vection can be experienced by virtually everybody and can be compelling to a point where observers reportedly cannot distinguish it from physical self-motion [1, 2, 11]. Yet, auditory vection tends to be much weaker and is only reported in 20-80% of blindfolded listeners [25], which might explain why it has received less attention in research and applications. Similar to visually-induced vection, auditory vection can be perceived for both rotational self-motion (e.g., circular vection around the earth-vertical axis), and for translational self-motions (linear vection) such as forward/backward motions.

Various stimulus characteristics have been shown to enhance auditory vection, resulting in earlier vection onset and increased vection intensity or convincingness ratings. Such vection-facilitating factors include increasing the number of moving sound sources [19, 27] and increasing the velocity of moving sound sources [7, 19, 27], although there seems to be an optimal stimulus velocity (around 60°/s for yaw circular vection) beyond which faster stimulus motion does not further enhance vection [5, 7]. While a minimum quality of sound spatialization is necessary to induce auditory vection, increasing sound spatialization or rendering quality further by using individualized (as compared to generic) head-related transfer functions or binaural recordings does not necessarily enhance vection further [12, 27].

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Besides physical stimulus characteristics, the meaning and interpretation of the moving sound sources can also matter. For example, sound sources associated with stationary "acoustic landmarks" such as church bells or fountain sounds were shown to be more effective in inducing auditory vection than sound sources associated with moving objects (e.g., vehicle sounds) or neutral sounds such as pink noise [8, 19, 26, 28]. Even a non-spatialized sound can induce auditory vection if it is perceived to have an inherent motion direction: Blindfolded listening to an ascending Shepard-Risset Glissando (i.e., a continuously rising pitch) resulted predominately in upward (elevator) vection, while descending glissandos elicited downwards vection [9]. One's own belief and perception of whether or not actual self-motion is possible can also modulate auditory vection [12]; it is likely one of the reasons why auditory vection researchers often seat listeners on rotation platforms, movement carts, or other platforms, suggesting that actual self-motion might be possible.

3 Multi-modal contributions of moving spatialized sound sources

Despite the fact that visual cues are typically much more effective in inducing vection than auditory cues, spatialized auditory cues that move in sync with a rotating visual stimulus can nevertheless be used to significantly enhance visually-induced circular vection [5, 6, 16, 20]. Similarly, adding rotating sound sources can also enhance "biomechanical" circular vection induced by blindfolded listeners stepping along a rotating floor platform above which they are seated stationary [17, 18]. Conversely, listening to stationary spatialized sound can reduce biomechanical vection [18]. That is, spatialized sound can both enhance circular vection induced by another modality (if consistent with that modality) and interfere with it (if inconsistent).

4 Multi-modal contributions of non-spatialized sounds

Even if auditory cues are not spatialized, they can under certain conditions enhance visually-induced vection if they metaphorically match the visually-presented self-motion. For example, non-spatialized sounds increasing or decreasing in pitch facilitated visually-induced upward and downward (elevator) vection, respectively, but did not affect visually-induced vection in other motion directions [22].

However, sound decreasing in volume (as if moving away) showed no clear effect on visually-induced vection, even though sound increasing in volume (as if moving closer) facilitated visually-induced forward vection [22]. Note that such metaphorical or higher-level/cognitive contributions might be prone to experimental demand characteristics as discussed in more detail in [10, 15].

5 Conclusions

Although auditory cues alone provide a much less compelling self-motion sensation than visual cues or biomechanical cues (from walking on a circular treadmill), they can significantly enhance vection induced by other modalities as well as enhance presence and immersion in virtual environments [3, 14, 16, 27]. Furthermore, they can provide omnidirectional cues beyond the limitation of the visual field of view or visual occlusion. This makes spatial sound a promising candidate for further enhancing numerous self-motion simulation applications ranging from immersive virtual reality to entertainment, movies, and tele-presence/tele-robotics; All the more so because high quality spatialized sound can be provided at relatively low cost, using either multi-speaker setups or headphones with HRTF convolution or binaural recordings. In fact, we posit that auditory virtual reality might be the best (and only true) virtual reality we can currently provide. High-quality sound renderings or recordings can not only be indistinguishable from real-world stimuli, but can also be provided by a "transparent interface". That is, while we tend to be aware we are looking at a display presenting visual VR cues, we can easily be unaware of the sound-producing device. In this sense, the ultimate VR system might not be visual, but auditory.

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