

SENSORIMOTOR INTEGRATION OF VESTIBULAR, PROPRIOCEPTIVE, AND VISUAL INFORMATION ABOUT HEAD MOTION IN THE INTERPRETATION OF DYNAMIC AUDITORY CUES FOR FRONT/BACK SOUND LOCALIZATION

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1 Introduction

Accurate perception of the location of a sound source is greatly facilitated by listener head rotation, which generates dynamic interaural time- and level-difference cues that differ between front- and rear-hemisphere sources. Those cues, however, specify front/back location only when coupled with information about the head motion that produced them. Potential sources of head-motion information for the auditory system are the vestibular, proprioceptive, and visual systems. To investigate the influence of these extra-auditory modalities on the interpretation of dynamic acoustic cues, we have examined dynamic localization performance using an oscillating chair apparatus that permits dissociation of head-on-body and head-in-space motion in combination with a pair of left/right-reversing prism glasses that provide incongruent visual motion information.

2 Methods

2.1 Study design and participants

The data reported here were obtained under various static and dynamic listening conditions. In each, in a within-subjects design, we measured listeners' ability to discriminate between front- and rear-hemisphere low-frequency noise targets while individual or multiple sources of head-movement information were minimized or eliminated and while vestibular and proprioceptive or vestibular and visual head-motion cues were placed in opposition. In total, 12 normally hearing adult listeners participated (6 females, 6 males, age = 23-49).

2.2 Stimuli

Sound stimuli were bursts of low-frequency noise (0.5-1 kHz) with 5-ms raised cosine onset and offset ramps. Low-frequency stimuli were used, as it has been demonstrated that dynamic cues are more salient for low-frequency stimuli, which typically cannot be localized accurately without head motion [1,2]. Bursts were presented at a mean level of 70 dB SPL and trial-by-trial level roving (± 5 dB) was applied. They were presented over attenuating insert earphones in virtual auditory space using individually measured head-related transfer functions (HRTFs). In dynamic conditions, HRTF

filters were updated and interpolated (using a TDT RX6 processor) at 60 Hz based on tracking of head and body orientation, as described below. On each trial, a stimulus was presented from one of three front (azimuth 0° or $\pm 22.5^\circ$) or three rear (azimuth 180° or $\pm 157.5^\circ$) locations in the horizontal plane. The bursts were gated by source, head-in-space, or head-on-body position as described below.

2.3 General procedure

In most conditions, participants were seated in an open-fronted wooden box/chair mounted on a motorized apparatus that, when activated, continuously oscillated the box $\pm 45^\circ$ about its vertical axis with a peak velocity of $50^\circ/\text{s}$. In some conditions, the participant's legs and body were immobilized with straps and foam with the head free to move, whereas in others the head was also immobilized. In all but the vestibular/visual opposition condition, the participants were blindfolded to remove visual motion cues. Circumaural hearing protectors were placed over the insert headphones to further reduce the sensation level of the motor noise.

Two sensors from a Polhemus FASTRAK system were used to measure head-in-space and body-in-space orientation, and the difference between those measurements was used to derive a head-on-body angle when required.

On each trial in dynamic conditions, as the listener oscillated their head or were oscillated in the box, stimuli were gated on and off as the appropriate position angle (head-in-space, or head-on-body) passed through a *spatial window* centred on 0° and with a width of 2.6, 5, 10, 20, or 40° . Wider windows provided greater access to dynamic localization cues. After hearing the stimulus, the participant indicated whether the source appeared to be in the front or the rear hemisphere by using a hand-held button box. In each motion condition, multiple trials were presented in pseudo-random order for each combination of source position, motion direction (leftwards or rightwards), and spatial window width. The proportion of correct front/rear judgements was computed for each spatial window width.

2.4 Listening conditions

The front/rear discrimination task was performed under the following listening conditions:

Active head rotation. With the motor deactivated and the head free, the participant actively oscillated the head from side-to-side. Trials in which the peak head velocity deviated by more than $15^\circ/\text{s}$ from $50^\circ/\text{s}$ were repeated. Stimuli were gated by head-in-space angle. In this condition the participant

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has access to vestibular and proprioceptive information about head movement.

Passive rotation. With the motor activated and the head immobilized, the participant was passively oscillated from side-to-side. Stimuli were gated by head-in-space angle. In this condition proprioceptive information was minimized and the participant had access primarily to vestibular information about head movement.

Counter-rotation. With the motor activated and the head immobilized, the participant's body was passively oscillated from side-to-side while they used their neck muscles to keep the head touching two fixed reference points. Stimuli were gated, and dynamic HRTF synthesis was driven, by head-on-body angle. In this condition vestibular information was minimized and the dynamic cues were consistent with proprioceptive information about head movement.

Static listening. 200-ms stimuli were presented without head, body, or source motion. This condition was included to demonstrate the difficulty of front/rear localization of the low-frequency noise stimuli in the absence of dynamic cues and to provide a baseline for assessing head-motion benefit.

"Dynastatic" listening. The participant sat without motion in a normal chair while the stimuli were gated, and dynamic HRTF synthesis was driven, by the orientation of a sensor placed on the activated (but empty) oscillating chair. This condition was included to demonstrate the difficulty of front/rear localization of the low-frequency noise stimuli in the presence of dynamic cues but in the absence of information about head motion.

Hemi-counter-rotation. To assess the relative dominance of vestibular and proprioceptive head-motion cues, they were placed in opposition. This condition was similar to the *counter-rotation* condition, but the support for the head-reference points was geared such that it rotated in the same direction as the chair but at $\sim 1/2$ the amplitude. Head-in-space and head-on-body angles were therefore opposite and approximately equal throughout the oscillation with peak velocities of $25^\circ/\text{s}$. HRTF synthesis and stimulus gating were driven by head-on-body angle.

Left/right reversed vision. To assess the relative dominance of vestibular and visual head-motion cues, the *passive* condition was repeated with the room lit and the blindfold removed. This was done once with normal visual input (congruent vestibular and visual information) and once while the participant wore left/right reversing prism goggles (opposed vestibular and visual information). Spatial windows of 10° and 20° were used.

3 Results

In Figure 1, performance in the *static* condition was near chance, but improved similarly with increasing spatial window width in the *active* and *passive* rotation conditions, in which vestibular information was available. Source motion (*dynastatic*) or isolated head-on-body motion (*counter-rotation*) did not provide a benefit. In the cue-opposition conditions (Figure 2), dynamic cues were typically

interpreted based on the vestibular head-in-space motion information.

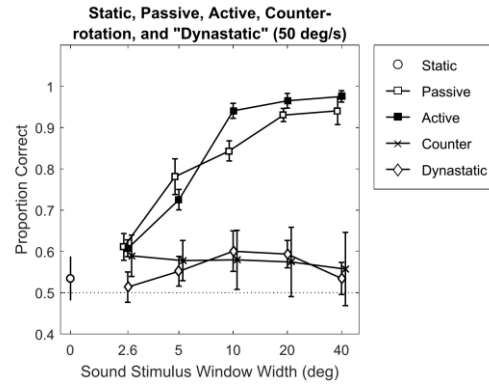


Figure 1: Mean front/rear performance for six participants in the motion-cue deletion conditions. Bars show standard errors.

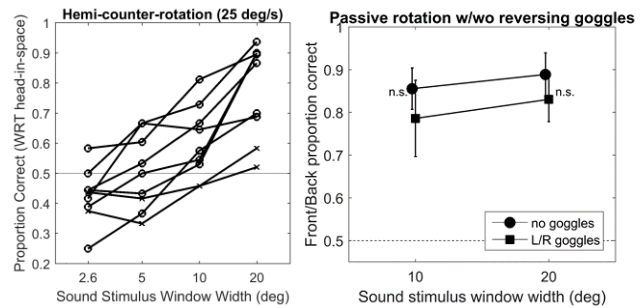


Figure 2: Left: Front/rear discrimination for nine participants in the vestibular/proprioceptive opposition condition. Right: Mean performance for five participants in the vestibular/visual opposition condition; no significant effect of reversed vision was observed.

4 Summary and conclusion

The results indicate that only vestibular head-motion information is necessary, sufficient and dominant in the interpretation of dynamic auditory cues for front/back sound localization, as summarized in Table 1.

Table 1:

Head-motion cue	Necessary	Sufficient	Dominant
Vestibular	✓	✓	✓
Proprioceptive	×	×	×
Visual	×	?	×

Acknowledgments

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References

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