I ed a e , S ec a Se V a A d S ace, P ceed g f he F contrast, as a source nears the head along the median plane, sound level changes very slowly with distance.

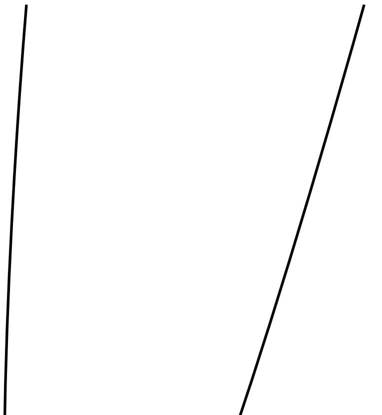

Figure 1: RMS pressure at the near ear as a function of source distance for sources at various directions in the horizontal plane. Lines show predictions for a spherical head model. Symbols show measured RMS pressure at the ear canal of a human subject.

These results show that the RMS pressure of the signals reaching the ears can provide distance information. However, since the absolute level of the direct sound varies both with distance and with the energy emitted from the source, the level at the ears can only provide *e a e* distance information unless the listener has a priori knowledge about the source level.

3.2 Interaural Level Differences

It is well known that level differences in the signals at the two ears (ILDs) can arise at moderate to high frequencies due to the acoustic interference of the head (e.g., see [15]). Such head shadow effects provide directional spatial information but are essentially invariant with source distance. However, when sources are close to (within a meter of) the head and laterally displaced from the median plane, changes in source distance cause changes in ILD across all frequencies [5, 9]. To a first-order approximation, these two sources of ILD (i.e., the head shadow and the direction- and distance-dependent ILD that can arise for near sources) are additive [20]. Thus, the total ILD can be broken down into the direction- and frequency-dependent, distance-independent head-shadow component (that is normally simulated in VAS) and a distance- and direction-dependent, frequency-independent component (that is normally overlooked).

Figure 2 shows how ILD varies with source distance for sources in various directions. As in Figure 1, results are shown for both a rigid, spherical head and for empirical measures from a human subject.

For both measured and theoretical results, a change in distance for a nearby source causes significant changes in the overall ILD when the source is to the side of the listener. For sources on the interaural axis, the ILD ranges over 20 dB as distance ranges from 1 m to 15 cm. While the change in the ILD with distance is roughly equivalent for theoretical and empirical results, the ILDs observed in empirical measurements are larger than predicted by the spherical head model (by approximately 5 dB). This discrepancy is primarily due to the fact that the RMS pressure measured at the far (shadowed) ear was consistently less than predicted by the spherical-head model (note, for instance, the agreement in the predicted and measured levels at the right, near ear in Figure 1). While the reason that the model overestimates the sound level at the far ear is not clear, it may be a result of a mismatch between the assumed head size in the model and the actual head size for the subject whose results are shown in Figure 2.

For sources in the median plane, ILD is essentially zero, independent of source distance. Additionally, when the source is more than about a meter from the head, changes in distance cause no significant change in ILD; for relatively large distances, only the

the head. In addition, the reverberant energy reaching the ears varies with source location relatively quiet and ILD cues may already provide distance information), reverberation yields drastic improvements in distance perception [17]. In fact, we observe reasonably good distance performance for sources in all directions (including along the median plane, where ILD cues are nonexistent and reverberant cues are relatively weak; see Figure 4), although performance is best for lateral sources.

While Brungart's results show that ILD cues can be useful in a true anechoic setting [4], recent results in our own laboratory call into question whether anechoic simulations employing ILD cues yield robust distance percepts [19]. Individually-measured transfer functions were used to simulate anechoic and reverberant listening conditions for both medial and lateral sources under headphones. Listeners judged source distance for both binaural and monaural listening conditions using roving-level noise stimuli. Distance performance for all anechoic conditions was at chance levels. In the reverberant conditions, subjects were able to extract distance information reliably. Surprisingly, reverberant monaural and binaural conditions yielded essentially equivalent performance. These results suggest that ILD cues (which are not available in monaural listening conditions) do not contribute to the perception of source distance when reverberation is present. Further, even when large ILDs are present in anechoic headphone simulations, they do not lead to robust distance percepts.

5. DISCUSSION

These results suggest that creating ILDs that vary with nearby source distance is not critical for simulating source distance in VAS. In contrast, overall level and reverberation cues provide compelling percepts of source distance in real-world listening conditions and under headphones.

Incorporating overall level effects into a VAS is straightforward and requires little computational power. In fact, both overall level and ILD cues can be approximated simply by adjusting the overall signal level at the left and right ears appropriately for the given source location [20]. In contrast, incorporating realistic reverberation into a display requires extensive computation [18]. Results discussed above suggest that binaural attributes in the reverberation are not critical to the perception of distance [19]. This may imply that shortcuts can be taken in modeling reverberation, since binaural differences in the reverberation have at best a minor impact on distance perception. Unfortunately, few studies address how the brain computes distance from reverberation and which attributes of reverberation are critical to perception.

6. ACKNOWLEDGEMENTS

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