USE OF ENTROPY TO QUANTIFY REAL WORLD LISTENING ENVIRONMENTS

AND EFFECTS ON LISTENING PERFORMANCE

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BACKGROUND

- Hearing aids show greater benefit in laboratory tests than they do in the real world [1]. Further, listening performance is poorer in real world environments than in laboratory tests [2]. Reasons for this are not entirely clear.
- One reason that listening performance might be worse and hearing aids less effective in the real world than in laboratory tests is because real world listening environments may be unpredictable, distracting, and contain varying amounts of information.
- In information theory, the amount of information in a system is a function of how predictable the system is [3]. Unpredictable systems contain more information than predictable systems.
- Entropy quantifies the predictability of a system. Systems with narrower probability density functions have lower entropy values (higher predictability) than systems with wide probability density functions (lower predictability) (**Figure 1**).

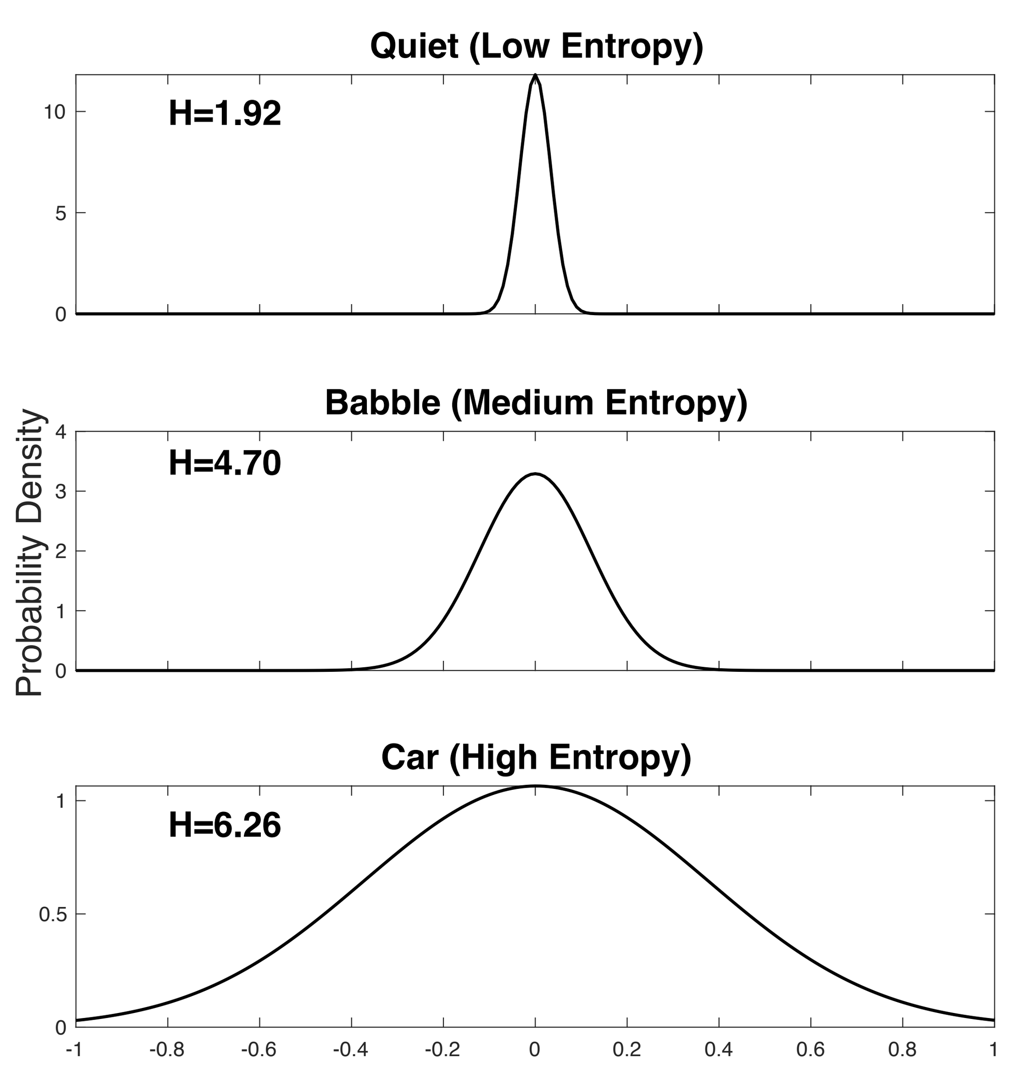

Figure 1: Examples of probability density functions and corresponding entropy values (H) of three listening environments.

- Entropy in listening environments can be measured in the time-domain by calculating the probability density function of acoustic energy and then estimating the entropy value. Environments with more complex background noise have higher entropy values. For example, as the occupancy of a cafeteria increases, so does the energy entropy [4].
- Higher entropy in the background noise may result in poorer listening performance, as higher entropy may result in greater distraction and more informational masking.
- **The primary purpose of this study was to investigate whether energy entropy affects listening performance in the real world**. We hypothesized that as entropy increases, listening effort increases and speech perception decreases. We hypothesized that these findings would hold even when signal-to-noise ratio was controlled.
- **The secondary purpose of this study was to investigate whether entropy was a better predictor of listening performance in the real world than environment type**. We hypothesized the entropy, rather than environment type, predicts listening performance.

METHODS

- A subsample of seven hearing aid users who wore hearing aids in four different primary conditions as well as practice and reliability conditions was taken from a larger study [1]. Listening effort ($F(6)$=.29, p=.94) and speech perception ($F(6)$=.54, p=.77) ratings did not differ between conditions. Conditions were combined.
- Participants completed surveys (Ecological Momentary Assessments, EMA) on smartphones and wore digital recorders around their neck (Language Environment Analysis, LENA) while wearing hearing aids in the real world **Figure 2**.

Figure 2. LENA device (top) and EMA application (bottom). Photo of LENA device from www.lena.org.

- EMAs asked participants to rate their speech perception and listening effort on a 100-point scale.
- Sound recordings were extracted from LENA devices and paired with EMAs. Recordings were single channel, 16-bit, sampling rate of 22050. One to three samples (~2-4 seconds) of noise (no signal, i.e. speech) of the environment were extracted, depending on recording quality.
- Sound recordings and EMAs in which participants indicated that they were not actively listening were excluded. Sound recordings were rated on a ten-point scale by trained listeners (1 being poorest quality and 10 being highest quality). Only recordings rated 10 were used in the analysis as audio quality was critical to accurate entropy estimations. In total, 91 samples were analyzed. Trained listeners classified recordings into one of nine environment types.
- From each recording, signal-to-noise ratio was estimated using the method detailed in [5].
- From each recording, entropy was estimated from a 2 second sample. The time-domain signal over 2 seconds was normalized and allocated to 100 bins. Energy entropy was estimated using the discrete entropy formula (below). Entropy was averaged across samples (if available).

$$H(X) = -\sum_{i=0}^{N-1} p_i log_2 p_i$$

Shannon entropy formula, where p_i is the individual probability of some event.

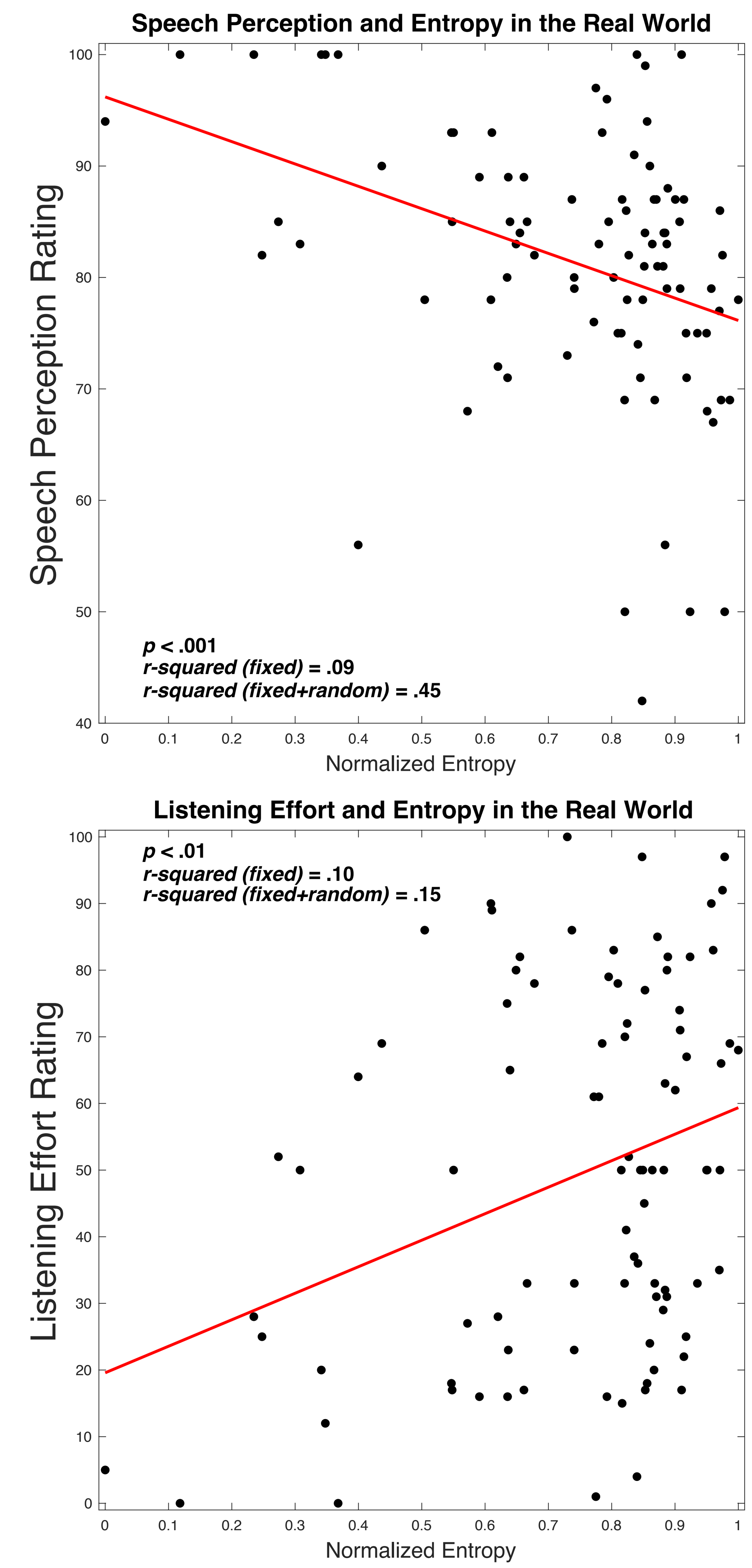

Figure 3. Effects of entropy on ratings of speech perception (top) and listening effort (bottom). Note: ordinates are not on the same scale.

RESULTS

- Linear mixed effects models with random intercepts for participants showed that **entropy significantly affected speech perception** (t(85.75)=-3.44, p<.001) **and listening effort** (t(88.70)=3.13, p=.002) ratings, although there was considerable variance and r^2 for fixed effects were small (**Figure 3**).
- **Entropy remained a significant predictor** of speech perception (t(84.72)=-2.63, p=.01) and listening effort (t(87.73)=-2.47, p=.02) ratings **when signal-to-noise ratio was controlled.** Signal-to-noise ratio was significant for speech perception (t(84.34)=2.15, p=.03) but not listening effort (t(87.77)=-1.77, p=.08) ratings. When models with both SNR and entropy were compared to models with only entropy, the model with both SNR and entropy explained significantly more variance in speech perception ratings (r^2=.48) than the model with entropy alone (r^2=.45, χ^2(1)=4.58, p=.03), but including SNR did not explain significantly more variance in listening effort ratings (r^2=.19) than entropy alone (r^2=.15, χ^2(1)=2.97, p=.08).
- **Environment type was not significantly associated with listening effort** (F(8)=.38, p=.93) **or speech perception** (F(8)=.79, p=.62) ratings (**Figure 4**). Entropy was also estimated for different environment types (**Figure 5**).

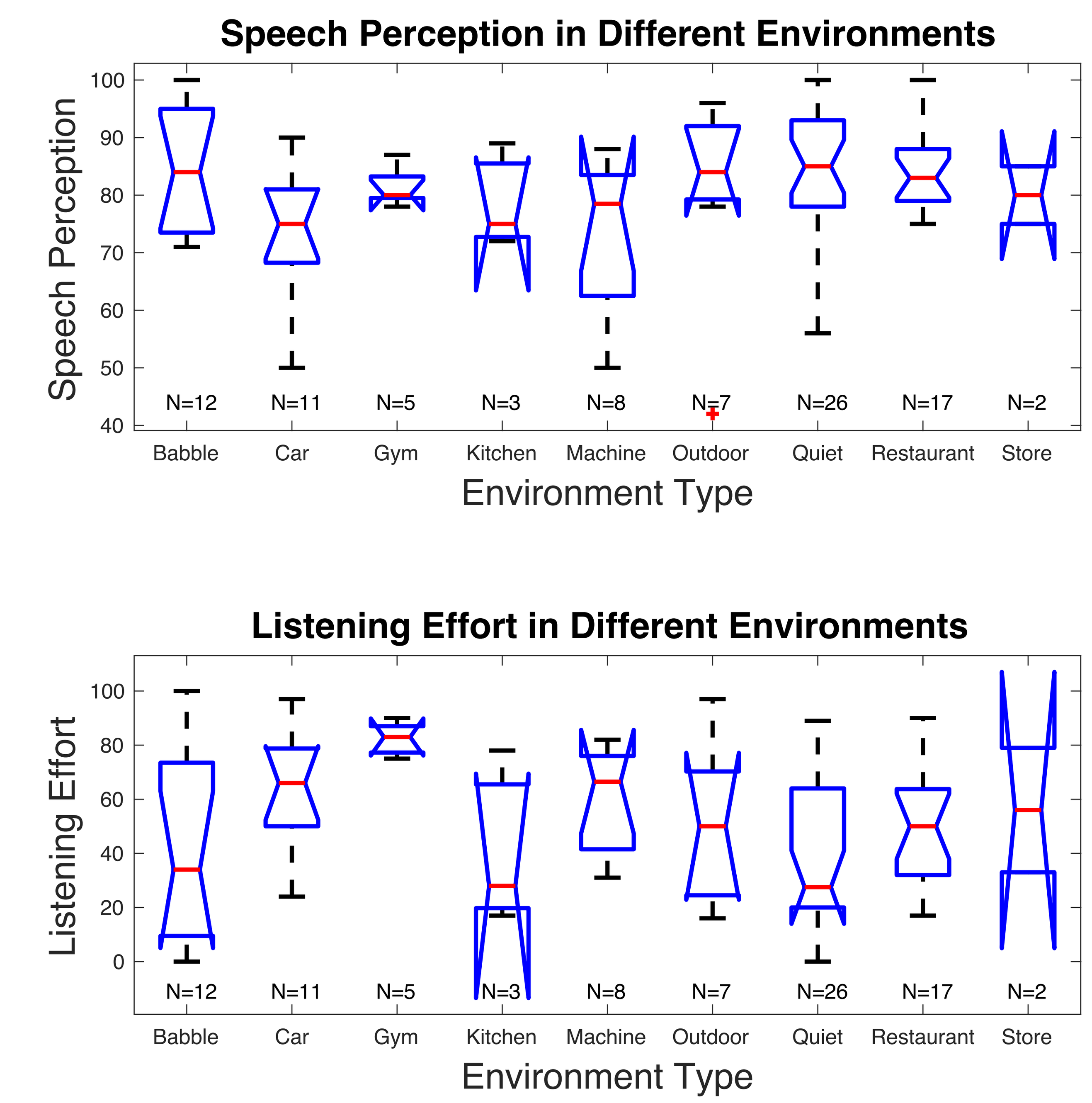

Figure 4. Speech perception (top) and listening effort (bottom) in different listening environment types. No significance differences between environments were found. Note the wide variance in (N) for each environment.

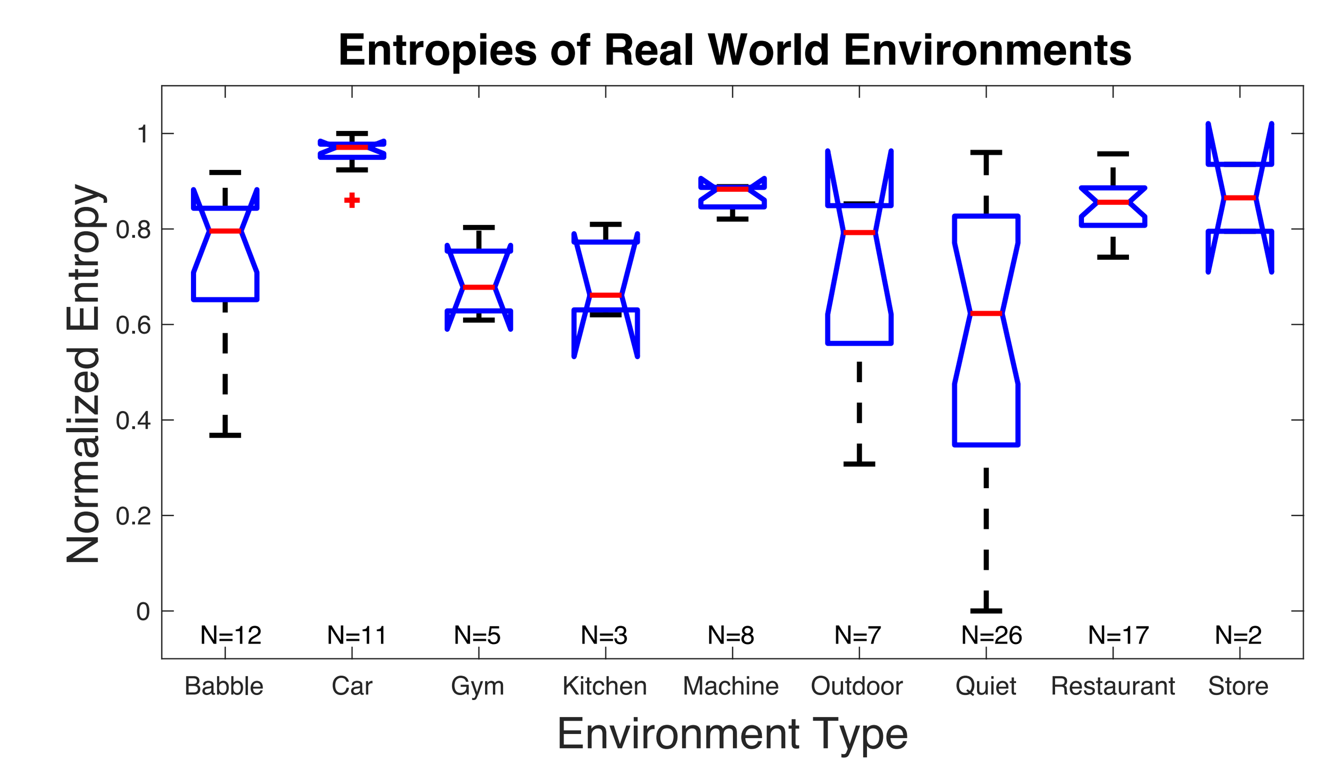

Figure 5. Entropies of different listening environment types.

DISCUSSION

- The findings from this study were consistent with our hypotheses. More complex environments, as quantified by entropy, yielded poorer listening performance. Listening environment type did not predict listening performance. Entropy varied considerably within environment type.
- Entropy remained a significant predictor of speech perception and listening effort even when signal-to-noise ratio was controlled.
- Differences in entropy may contribute to differences in hearing aid effectiveness and listening performance between laboratory and real world environments.
- Entropy only accounted for a small part of the variance in the data. The likely reason for this is that listening effort and speech perception in the real world are affected by many factors that were not accounted for in this analysis.

References: [1]Wu et al. EH. 2019, 40(4), 805-822. [2]Best et al. IJA. 2015, 54(10), 682-690. [3]Shannon, C. Bell System Technical Journal. 1948, 27(3), 379-423. [4]Ghozi et al. JAES. 2015, 63, 475-487. [5]Wu et al. EH. 2018, 39(2):293-304.

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