Hybrid stimuli intervals were replaced by noise than when low-CSE intervals were replaced, consistent with Stilp et al. (2013), Stilp (2014), and Stilp and Goupell (2015).

EAS benefit (RAU improvement for hybrid condition relative to vocoded condition) varies with stimulus condition:
- For continuous sentences, EAS benefit decreases with more spectral channels.
- For noise-interrupted sentences, EAS benefit increases with more spectral channels.
- No benefit at 3-4 channels, comparable significant benefits across CSE conditions at 5-6 channels.
- EAS benefit does not interact with CSE conditions.

Perceptual Importance of CSE
- Decrement from control performance reveals the perceptual importance of the speech in sentence intervals that were replaced by noise.
- Larger decrements indicate greater importance of the replaced speech.

Vocoded
- Decrement are fairly flat across 3-6 spectral channels.
- Stilp and Goupell (2015) reported similar results for 4 channels but for larger decrements for high-CSE sentences with 6 channels.

Hybrid
- Largest decrements with few spectral channels.
- May be due to abolishing EAS benefit rather than high-CSE importance.
- Small decreases with more channels.
- Ceiling effects for continuous conditions may be contributing to smaller decrements.

The present data provide no evidence that listeners rely on CSE in vocoded versus hybrid speech.
- Information-bearing acoustic changes produced different patterns of decrements, but this could be due to abolishing the EAS benefit for 3-4 channel sentences. It made little difference whether low-CSE or high-CSE intervals were replaced.
- CSE is a measure of broadband spectral change, and this often captures changes in the speech envelope. Envelope information is relatively consistent across full-spectrum and vocoded speech (Stilp et al., 2013). This congruence may explain the lack of interactions between CSE and vocoder / hybrid conditions, as information-bearing acoustic changes do not differ very much across these processing conditions.
- The intact low-frequency channel (<500 Hz) was not weighted differently from noise-vocoded channels in CSE calculations. Future research will consider frequency-specific weighting in CSE calculations to reflect EAS benefit.

REFERENCES

INTRODUCTION
- Information-bearing acoustic changes in the speech signal are important for understanding speech. This has been demonstrated using cochlear-scaled entropy in simulated cochlear implant speech (CSE), which measures short-term spectral changes calculated across all channels of noise-vocoded speech. (Stilp et al., 2013, Stilp, 2014, Stilp & Goupell, 2015).
- Poorer sentence intelligibility occurred when high-CSE intervals were replaced by noise as compared to replacing low-CSE intervals.
- Speech intelligibility for CI users is often aided by preserved low-frequency cues in the non-implemented ear (Electric-Acoustic Stimulation, or EAS; Kong, et al., 2005; Kong & Carlston, 2007).
- While listeners are known to benefit from the addition of low-frequency intant to vocoded speech (hybrid hearing), it is unclear how they rely on information-bearing acoustic changes from the two different sources (intact low frequencies, vocoded higher frequencies).
- Here, we investigated the perceptual importance attributed to information-bearing acoustic changes in vocoded versus hybrid speech with relatively few spectral channels (conditions which were not systematically studied previously).

METHODS
Participants: 37 native English speakers ages 18-35; normal hearing confirmed via hearing screening.
Stimuli: *IEEE sentences spoken by female talker.
- Spectrum divided into 3-6 channels using Greenwood (1990) spacing.
- Amplitude envelopes extracted and assigned to white Gaussian noise.
- Vocoder stimuli: noise-channel vocoding from 80 to 8000 Hz.
- Hybrid stimuli: low-pass-filtered intact speech (<500 Hz) combined with high-pass-filtered vocoded speech (>500 Hz).
- CSE calculation:
  - CSE = Euclidean distances between RMS-amplitude profiles of successive 16 ms sentences, summed into 80 ms intervals.
- Same calculations performed for vocoded and hybrid sentences.
- In each sentence, four 80 ms intervals with high- or low-CSE were replaced with speech-shaped noise; continuous sentences had no noise replacement.
Procedure:
- Training:
  - Familiarization (passive listening) followed by training (testing with feedback).
  - Baseline testing: criterion of ≥27% on 3-channel vocoded sentences or ≥31% on 4-channel vocoded sentences.
  - Listeners failed to meet criteria, did not participate in testing.
- Testing:
  - CSE levels tested at two levels of spectral resolution (3/5 or 4/6, or 12 in each) EAS (vocoder/hybrid) counterbalanced across sessions.
  - Mixed design employed due to limited number of IEEE sentence list: Within-subjects factors: CSE, CSE, and listeners.
  - Between-subjects factor: higher (4/6 channels) vs. lower (3/5) numbers of vocoder channels.
  - Stimuli presented dichotically at 70 dB SPL.

Main Findings
- Results were cosine transformed (Studebaker, 1985) for analysis. Analysis used within-subjects ANOVA (comparing performance at 3 vs. 5 channels, or 4 vs. 6 channels) or mixed ANOVA (comparisons across listener groups) and corresponding paired-samples or independent-samples t-tests. Statistically significant differences are indicated by *.
  - In general, performance was impaired more when high-CSE intervals were replaced by noise than when low-CSE intervals were replaced, consistent with Stilp et al. (2013), Stilp (2014), and Stilp and Goupell (2015).
  - EAS benefit (RAU improvement for hybrid condition relative to vocoded condition) varies with stimulus condition:
    - For continuous sentences, EAS benefit decreases with more spectral channels.
    - For noise-interrupted sentences, EAS benefit increases with more spectral channels.
    - No benefit at 3-4 channels, comparable significant benefits across CSE conditions at 5-6 channels.
    - EAS benefit does not interact with CSE conditions.

DISCUSSION
Listeners are able to use information-bearing acoustic changes to understand hybrid speech:
- For sentences with 5 and 6 channels, performance suffers more when high-CSE intervals are replaced by noise than when low-CSE intervals are replaced.
- A similar pattern was observed for vocoded speech, consistent with Stilp and Goupell (2015).
  - For sentences with very few (3-4) spectral channels, listening mode and information-bearing acoustic changes had little effect on performance:
    - Large EAS benefit when sentences are intact; near-zero EAS benefit when sentences are interrupted by noise.
    - Performance only slightly worse when high-CSE intervals were replaced as compared to replacing low-CSE intervals.
  - Similar to Stilp and Goupell (2015), listeners utilized information-bearing acoustic changes to facilitate recognition of 6-channel sentences, but no differences were observed for 4-channel sentences.
  - This is despite differences in materials (IEEE vs. TIMIT sentences) and procedure (training with feedback versus virtually no practice).

The present data provide no evidence that listeners rely on CSE differently in vocoded versus hybrid speech.
- Information-bearing acoustic changes produced different patterns of decrements, but this could be due to abolishing the EAS benefit for 3-4 channel sentences. It made little difference whether low-CSE or high-CSE intervals were replaced.
- CSE is a measure of broadband spectral change, and this often captures changes in the speech envelope. Envelope information is relatively consistent across full-spectrum and vocoded speech (Stilp et al., 2013). This congruence may explain the lack of interactions between CSE and vocoder / hybrid conditions, as information-bearing acoustic changes do not differ very much across these processing conditions.
- The intact low-frequency channel (<500 Hz) was not weighted differently from noise-vocoded channels in CSE calculations. Future research will consider frequency-specific weighting in CSE calculations to reflect EAS benefit.

On the Importance of Information-Bearing Acoustic Changes for Understanding Speech in Simulated Electrical-Acoustic Stimulation
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