Current clinical stimulation strategies for cochlear implants (CI) disregard temporal fine structure information, which has been shown to be important for lateralization of sound sources in normal hearing (Smith et al., 2002). While a number of studies investigated the sensitivity of bilateral CI listeners to interaural time differences (ITDs) in continuous and modulated pulse trains (e.g. van Hees and Tyler, 2005), the specific contribution of ITD to the temporal fine structure has not yet been studied. In particular, the influence of onset and offset ITD cues has not been considered.

The relative contributions of fine structure, onset, and offset ITD for lateralization discrimination were studied at four pulse rates, using trains of four equal amplitude pulses. These results have the advantage that the effects of fine structure and onset/offset ITD can be compared across pulse rates without confounding variations of pulse number and pulse amplitude. An additional experiment verified that lateralization performance in experiment I was indeed mediated via binaural processing and not influenced by monaural cues. Both bilateral CI listeners and normal hearing (NH) subjects were tested.

**Subjects and implanted system**
- Three postlingually deafened, bilaterally implanted CI listeners, supplied with C40-003 models (Oticon Medical, Paris, France), were included in the study. Stimulus parameters were identical across subjects.

**Stimulus presentation**
- Each stimulus train was presented via two synchronized Research Interface Boxes (RIB, University of Bern, Switzerland), generating time differences up to 2.5 μs.
- The train of equal-amplitude biphasic current pulses (pulse duration: 26.7 μs) was presented as alternating monaural (left or right) or binaural stimulation.

**Acoustic analysis**
- Digital stimuli generation
- Use of digital filters to design a double-voided sound bowl
- Monophasic pulses (duration: 13 μs), filtered with a bandpass filter (-3 dB cutoff frequencies: 500 and 5000 Hz)
- Filtered bandwidth was chosen to preserve modulations and narrow enough to approximate the range of monaural activity in single electrode stimulation
- Continuous, infinitely-brief pink noise (500-1000 Hz) suprathreshold level of 52.5 SPL (40-60 dB HL) to avoid sensation of combination tones

**Methods**

1. Subjects and implanted system
   - Three postlingually deafened, bilaterally implanted CI listeners, supplied with C40-003 models (Oticon Medical, Paris, France), were included in the study. Stimulus parameters were identical across subjects.

2. Apparatus and stimuli
   - Electrical stimulation: two synchronized Research Interface Boxes (RIB, University of Bern, Switzerland), generating time differences up to 2 μs (left or right channeled to the contralateral ear)
   - Pulse presentation via two synchronized Research Interface Boxes (RIB, University of Bern, Switzerland), generating time differences up to 2 μs (left or right channeled to the contralateral ear).

3. Procedure for experiment I: Lateralization discrimination
   - Lateralization discrimination task: two-alternative forced choice (2AFC).
   - Internal reference stimuli (without ITD), 2nd internal: target stimulus (with ITD).
   -Subjects were asked to indicate the direction of the second stimulus which was closest to the right or left of the stimulus.

4. Procedure for experiment II: Nonmonaural discrimination
   - Discrimination task (2AFC): “l Madonna task”
   - Visual response feedback

5. Stimulus conditions
   - Pulse rate: 100, 200, 300, 400, and 800 pulses per second (pps)
   - Sequence of pulse trains: Continuous (70% of all rates), random order (30% of all rates)
   - Constant pulse amplitude for all pulse rates
   - Constant pulse amplitude for all pulse rates
   - NH: rise time 60 μs SPL (measured with continuous pulse train in 100 pps)
   - CI: rise time 50 μs SPL (measured with continuous pulse train in 100 pps)
   - 30% CH_{30%} (continuous presentation of 30% of all rates)

   **Experiment I:**
   - ITDs: Waveform delay (WFD), Fine structure delay (FSD), Gating delay (GD), Offset delay (OND) (Fig. 1b)
   - Experiment II:
     - Monophasic presentation of signals and condition of experiment I (exception: WD)
     - CI: fine structure delay (FSD) and pulse rate, corresponding to the binaural (left vs. right)

   **Experiment II:**
   - Monophasic presentation of signals and condition of experiment I (exception: WD)
   - CI: fine structure delay (FSD) and pulse rate, corresponding to the binaural (left vs. right)

6. Results
   - Significant main effects of ITD type (p<0.001), pulse rate (p<0.001), and subject group (p<0.001)
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   - Significant main effects of ITD type (p<0.001), pulse rate (p<0.001), and subject group (p<0.001)
   - Significantly different ITD type vs. pulse rate (p<0.001), ITD type vs. subject group (p<0.001), CI vs. NH (p<0.001)
   - CI listeners showed significantly higher sensitivity than NH listeners (p<0.001)
   - CI listeners showed significantly higher sensitivity than NH listeners (p<0.001)
   - CI listeners showed significantly higher sensitivity than NH listeners (p<0.001)

7. Conclusion
   - CI listeners are sensitive to fine structure ITD (without onset and offset ITD cues)
   - Sensitivity for CI listeners exceeds that of NH listeners (Sensitivity for CI listeners: 80% correct; Sensitivity for NH listeners: 50% correct)
   - CI listeners show significantly higher performance than NH listeners (p<0.001)
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8. Conclusions
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9. Discussion
   - CI listeners show significantly higher performance than NH listeners (p<0.001)
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10. Implications
    - CI listeners are sensitive to fine structure ITD (without onset and offset ITD cues)
    - Sensitivity for CI listeners exceeds that of NH listeners (Sensitivity for CI listeners: 80% correct; Sensitivity for NH listeners: 50% correct)
    - CI listeners show significantly higher performance than NH listeners (p<0.001)

**Acknowledgments**
- We thank the CI listeners for their enthusiastic participation in this study.

**References**
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**Highlights**
- CI listeners are sensitive to fine structure ITD (without onset and offset ITD cues)
- Sensitivity for CI listeners exceeds that of NH listeners (Sensitivity for CI listeners: 80% correct; Sensitivity for NH listeners: 50% correct)
- CI listeners show significantly higher performance than NH listeners (p<0.001)
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**Table 1**

<table>
<thead>
<tr>
<th>Pulse Rate (pps)</th>
<th>JNDs for CI listeners</th>
<th>JNDs for NH listeners</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>CI: 66% JND (µs)</td>
<td>NH: 73% JND (µs)</td>
</tr>
<tr>
<td>200</td>
<td>CI: 56% JND (µs)</td>
<td>NH: 67% JND (µs)</td>
</tr>
<tr>
<td>300</td>
<td>CI: 46% JND (µs)</td>
<td>NH: 55% JND (µs)</td>
</tr>
<tr>
<td>400</td>
<td>CI: 36% JND (µs)</td>
<td>NH: 45% JND (µs)</td>
</tr>
<tr>
<td>500</td>
<td>CI: 26% JND (µs)</td>
<td>NH: 35% JND (µs)</td>
</tr>
<tr>
<td>600</td>
<td>CI: 16% JND (µs)</td>
<td>NH: 24% JND (µs)</td>
</tr>
<tr>
<td>700</td>
<td>CI: 7% JND (µs)</td>
<td>NH: 7% JND (µs)</td>
</tr>
<tr>
<td>800</td>
<td>CI: 0% JND (µs)</td>
<td>NH: 0% JND (µs)</td>
</tr>
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</table>

Note that the JNDs for the three subjects are shown as a function of pulse rate. The error bars indicate ±1 standard deviation.