Speech and melody recognition in binaurally combined acoustic and electric hearing

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Speech recognition in noise and music perception is especially challenging for current cochlear implant users. The present study utilizes the residual acoustic hearing in the nonimplanted ear in five cochlear implant users to elucidate the role of temporal fine structure at low frequencies in auditory perception and to test the hypothesis that combined acoustic and electric hearing produces better performance than either mode alone. The first experiment measured speech recognition in the presence of competing noise. It was found that, although the residual low-frequency (<1000 Hz) acoustic hearing produced essentially no recognition for speech recognition in noise, it significantly enhanced performance when combined with the electric hearing. The second experiment measured melody recognition in the same group of subjects and found that, contrary to the speech recognition result, the low-frequency acoustic hearing produced significantly better performance than the electric hearing. It is hypothesized that listeners with combined acoustic and electric hearing might use the correlation between the salient pitch in low-frequency acoustic hearing and the weak pitch in the envelope to enhance segregation between signal and noise. The present study suggests the importance and urgency of accurately encoding the fine-structure cue in cochlear implants.

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I. INTRODUCTION

Cochlear implants have successfully restored partial hearing in severely hearing-impaired individuals. Recent studies have reported that many implant users can recognize 70%–80% of sentences presented in quiet. However, understanding speech in noise and music appreciation still remains a challenge for most implant users, due to the limitations of the electrode design and the signal processing scheme employed in current cochlear implants.

The poor speech perception in noise and music appreciation in cochlear-implant listeners are mainly due to their inability to encode pitch. The limited spectral resolution, especially the inaccurate encoding of low-frequency information, is believed to be the main reason for their poor pitch perception performance. Low-frequency information is important for both musical and voice pitch perception. It has been shown that speech recognition in the presence of a competing talker can be achieved by segregating the components of each voice using the fundamental frequency ($F0$) as a cue. Brokx and Nooteboom (1982) showed that listeners could identify the keywords in sentences more accurately against a background of competing speech by increasing the difference in $F0$. The $F0$ cue was shown to be effective in segregating competing voices even at low signal-to-noise ratios when the target speech did not show distinct peaks in the spectrum (Summerfield and Culling, 1992).

A pitch percept in normal auditory system can be elicited by either the place mechanism with resolved low-numbered harmonics or by the temporal mechanism following the temporal fine structure of the input signal. However, both pitch encoding mechanisms fail in current cochlear implants. The low-frequency information is neither appropriately represented by the place of stimulation nor by the temporal fine structure of the neural firing pattern. First, the relatively shallow insertion depth of present electrode arrays severely limit the transfer of low-frequency spectral information. The average insertion depth for the Nucleus implant was estimated to be 20 mm (Ketten *et al.*, 1998), which corresponds to the acoustic frequency lower limit of about 1000 Hz (Greenwood, 1990). Even with the latest electrode designs (such as the Clarion HiFocus, Nucleus Contour, and Med-El Combi40+), which are intended to provide a deeper insertion of up to 30 mm, there is still no guarantee that

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low-frequency neurons can be stimulated due to both reduced nerve survival in deafened individuals and non-tonotopic distribution of low-frequency neurons in the cochlea (Nadol *et al.*, 1989; Linthicum *et al.*, 1991). Second, low-frequency temporal information is not appropriately encoded in current speech processing strategies. All current coding strategies, except for the analog-based strategies such as the Compressed Analog (CA, Eddington, 1980) and Simultaneous Analog Stimulation (SAS, Kessler, 1999), extract only the temporal envelope of incoming signals from 6 to 22 frequency bands using a low-pass filter with a cutoff frequency below 500 Hz and amplitude modulate it to a fixed-high-rate pulsatile carrier. In these strategies, the low-frequency temporal information, namely the slowly-varying envelope ($<$50 Hz) and the periodicity cues (50–500 Hz) (Rosen, 1992), can be preserved in the temporal envelope, but they are encoded in the "wrong places," i.e., locations in the cochlea that are tuned to higher frequencies. Furthermore, fine structure information of the input signal, which is the phase information defined mathematically by the Hilbert transform (Hilbert, 1912), is discarded in such processing schemes due to the usage of a fixed-rate carrier. While the low-frequency information conveyed by the temporal envelope can support speech recognition in quiet (e.g., Shannon *et al.*, 1995), it is not sufficient to support speech recognition in noise with limited spectral cues (e.g., Fu *et al.*, 1998; Zeng and Galvin, 1999; Qin and Oxenham, 2003; Stickney *et al.*, 2004) and robust pitch perception (e.g., Burns and Viemeister, 1981; Green *et al.*, 2002; Kong *et al.*, 2004).

As the audiological criteria for implant candidacy have become less stringent, individuals with substantial residual low-frequency hearing have received cochlear implants. Recent development of short-electrode arrays allows the preservation of low-frequency acoustic hearing in these patients (von Ilberg *et al.*, 1999; Gantz and Turner, 2003). For those who are implanted with the conventional long-electrode arrays, low-frequency acoustic information is also available by combining electric hearing with acoustic hearing from the nonimplanted ear (Dooley *et al.*, 1993; Tyler *et al.*, 2002). Availability of these individuals allows a unique opportunity to study the role of fine-structure information at low frequencies in auditory perception, particularly in tasks that depend on pitch perception (i.e., music perception and speech recognition in the presence of a competing talker).

Previous studies on speech perception with binaurally combined acoustic and electric hearing revealed mixed results (for adults, see Dooley *et al.*, 1993; Armstrong *et al.*, 1997; Tyler *et al.*, 2002; Ching *et al.*, 2004; for children, see Chmiel *et al.*, 1995; Ching *et al.*, 2001). Chmiel *et al.* (1995) reported significantly better speech performance in quiet with a combined use of hearing aids and cochlear implants in three of the six subjects. Similar results were also reported by Armstrong *et al.* (1997) and Ching *et al.* (2001 and 2004), showing better sentence and phoneme recognition performance with combined acoustic and electric hearing in both quiet and in multi-talker babble noise at a 10 dB signal-to-noise ratio. Anecdotally, some implant users reported that the additional low-frequency acoustic information improved both sound quality and sound localization (Armstrong *et al.*, 1997; Tyler *et al.*, 2002). Moreover, two of the three subjects tested in Tyler *et al.* (2002) reported that the acoustic and electric signals fused to form one integrated sound image. Potential incompatibility between acoustic and electric hearing has also been reported. For example, Tyler *et al.* (2002) reported that one of their subjects heard the acoustic and electric stimuli as separate sound sources. Blamey *et al.* (1996 and 2000) demonstrated a pitch mismatch and differences in the dynamic range and the shape of the iso-loudness curves between the acoustically and electrically stimulated ears. Dooley *et al.* (1993) also reported that some subjects discontinued using their hearing aids or cochlear implants after implantation. However, for those patients who adapted to both devices, the incompatibility between the two percepts did not seem to interfere with their speech recognition in both quiet and noise (Dooley *et al.*, 1993; Tyler *et al.*, 2002).

The first study by von Ilberg *et al.* (1999) on combined acoustic and electric hearing with specially designed short-electrodes showed better speech recognition in quiet with the additional low-frequency acoustic hearing compared to electric hearing alone. The range of improvement was 4 to 70 percentage points depending on the filtering configuration of the cochlear implant. A recent study by Turner and colleagues (2004) on short-electrodes also showed significant benefits of additional low-frequency acoustic hearing in speech recognition in noise. They compared the speech reception thresholds of spondee words in different noise backgrounds (steady-state noise versus competing sentences) in implant users with "short-electrodes" and traditional "long-electrodes." They reported that speech reception thresholds improved by 15 dB in the competing talker background and 5 dB in the steady-state noise background in combined hearing recipients with the short-electrode implants compared to the traditional long-electrode users. They concluded that the better speech recognition performance in multi-talker babble noise with the additional low-frequency acoustic hearing was attributed to the ability of the listeners to take advantage of the voice differences between the target and the masker speech.

One of the reasons that current cochlear implant listeners have great difficulty in understanding speech in a fluctuating background of other talkers (Nelson *et al.*, 2003; Stickney *et al.*, 2004) is their impaired pitch perception ability. The goal of the present study was to investigate how residual low-frequency hearing from the nonimplanted ear provides information that is necessary for pitch perception, and in turn improves speech and music perception in cochlear implant listeners. Two experiments were conducted to reveal the role of low-frequency acoustic hearing in realistic listening situations that are exceptionally challenging for cochlear implant users. The first experiment was designed to evaluate speech recognition in the presence of another speech sound in three listening conditions: hearing aid (HA) alone, cochlear implant (CI) alone, and cochlear implant plus hearing aid (CI +HA). The second experiment was designed to evaluate melody recognition with primarily pitch cues in cochlear-implant users in the same three listening conditions. We hypothesized that the additional low-frequency acoustic infor-

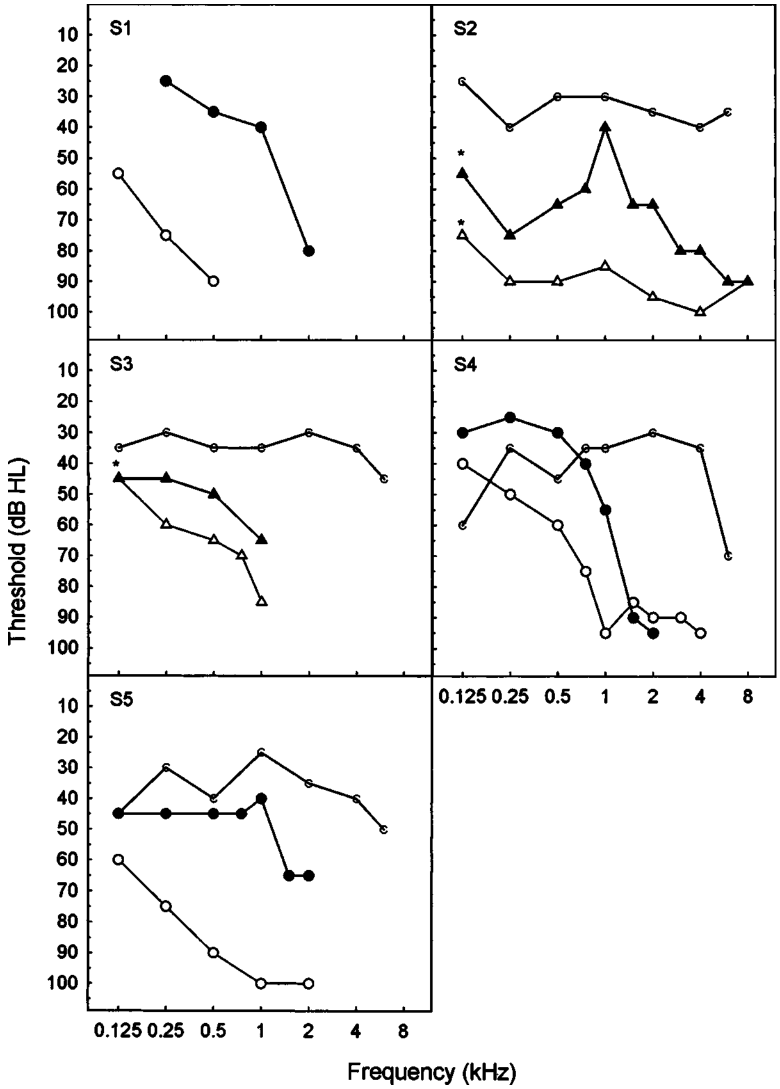

FIG. 1. Aided (closed symbols) and unaided (open symbols) thresholds in the nonimplanted ear (circles for the right ear; triangles for the left ear) and cochlear implant ear (indicated as "C"). Only thresholds at or below 100 dB HL were shown. The asterisk above the symbol indicates vibrotactile response. Implant thresholds in subject S1 were not obtained.

mation from the nonimplanted ear would provide more accurate pitch information to aid perceptual segregation of competing voices and to contribute significantly to musical pitch perception.

II. SPEECH RECOGNITION IN NOISE

A. Methods

1. Subjects

Four cochlear-implant subjects with significant residual acoustic hearing in the nonimplanted ear were recruited to participate in this study. They were two females and two males, with ages ranging from 49 to 79. Figure 1 shows their aided and unaided thresholds in the nonimplanted ear and the thresholds in the implanted ear. Their unaided thresholds showed moderate to profound loss at frequencies from 125 to 8000 Hz, but their aided thresholds showed only mild to severe loss at frequencies at or below 1000 Hz. The aided threshold averaged over 125, 250, and 500 Hz was 30, 70, 48, and 28 dB HL for subjects S1, S2, S3, and S4, respectively. While all other subjects had better aided thresholds below 1000 Hz, subject S2 had the lowest threshold (40 dB HL) at 1000 Hz and poorer thresholds below 1000 Hz. Thresholds from the cochlear implant for subjects S2, S3, and S4 were between 25 and 70 dB HL from 125 to 6000 Hz. The implant thresholds for S1 were not tested. Three out of the four subjects (S1, S3, and S4) continued to use their hearing aids on a daily basis, whereas S2 discontinued using his hearing aid after implantation in spite of residual hearing in the nonimplanted ear. Subject S2 did not use his hearing aid because of poor speech recognition rather than any perceived incompatibility between his hearing aid and cochlear implant.

All subjects were postlingually deafened and had at least one year of implant usage at the time of the test. They were native speakers of American English. Table I shows additional information regarding hearing history and implant type. Two subjects had the Clarion device, with S1 having the Clarion precurved electrode and S2 having the Clarion Hi Focus II with the positioner. The remaining two subjects (S3 and S4) used the Nucleus 24 device. Subject S1 used two different speech processing strategies: simultaneous analog stimulation (SAS) and multiple pulsatile sample (MPS), depending on the listening situations. Subject S2 and S4 used the continuous interleaved sampling (CIS) strategy, and S3 used the advanced combination encoder (ACE) strategy.

TABLE I. Biographical information on five cochlear-implant subjects.

Subject	Age[a]	Mus.[b]	Age onset[c]	Etiology	Yrs. exp.[d]	Device[e]	Strategy[f]	HA use[g]	Consonant[h] (%)	Vowel[i] (%)
S1	49	>20	4	Unknown	4	Clarion precurved	SAS/MPS	Y	46/54	51/40
S2	50	0	25	Unknown	2	Clarion HiFocus II	CIS	N	86	68
S3	69	0	37	Unknown	3	Nucleus 24	ACE	Y	54	51
S4	79	0	36	Unknown	1	Nucleus 24	CIS	Y	58	45
S5	19	0	3	Unknown	3	Clarion precurved	SAS	Y	41	33

[a]Age of the subject at the time of the experiments.
[b]Years of formal musical training.
[c]Age at the onset of hearing loss.
[d]Years of experience with the implant.
[e]Implant type.
[f]Processing strategy in the speech processor used during the experiments.
[g]Consistent use of hearing aid in the nonimplanted ear after implantation.
[h]Score (% correct) on consonant recognition in quiet in /aCa/ context.
[i]Score (% correct) on vowel recognition in quiet in /hVd/ context.

2. Stimuli

A subset of IEEE sentences (1969) recorded by Hawley *et al.* (1999) was used in this experiment. Each list consisted of ten sentences with five keywords per sentence. The target sentence was spoken by a male voice. Another sentence (competing sentence) spoken by a different male talker or by a female talker was used as a masker. The same competing sentence was used throughout testing (''Port is a strong wine with a smoky taste''). The target sentence was either presented alone or in the presence of the masker. The target and masker had the same onset, but the masker's duration was always longer than the target sentence. The target sentence was presented at approximately 65 dBA whereas the level of the masker varied from 45 dB to 65 dBA to produce five signal-to-noise ratios (SNR): +20, +15, +10, +5, and 0 dB.

3. Procedure

Subjects were evaluated under three listening conditions: hearing aid (HA) alone, cochlear implant (CI) alone, and cochlear implant with hearing aid (CI+HA). The subject's cochlear implant was turned off in the HA alone condition, and their hearing aid was turned off and the nonimplanted ear was plugged in the CI alone condition. These three listening conditions were evaluated in random order for each subject.

All tests were performed in a double-walled sound-treated booth. Both the target and masker sentences were presented via a loud speaker directly in front of the subject. Subjects used their own hearing aid and cochlear implant volume and sensitivity settings during the entire test session. All subjects were tested with the male masker, with subjects S2, S3, and S4 also being tested in a second test session with the additional female masker. S1 was not available for the second test session with the female masker. Prior to the test session, subjects were presented with two practice sessions of ten sentences each binaurally. In the first practice session, subjects were presented with sentences in quiet. The second practice session was used to familiarize listeners listening to the target sentence in the presence of the masker. In this practice session, two sentences were presented for each of the five SNR conditions used in the actual experiment. In the test session, each subject was presented with all five SNR conditions in a random order. There were 10 randomized sentences (5 keywords each), for a total of 50 keywords per SNR and 50 sentences for the test session. The subjects typed their responses at the keyboard and were encouraged to guess if unsure. Responses were collected and scored in terms of the number of words correctly identified using MATLAB software.

B. Results

Figure 2 shows percent correct scores as a function of SNR for sentence recognition in the presence of the male masker for both individual and average data (bottom right panel). Panels S1a and S1b represent results from subject S1 using the SAS and the MPS strategy, respectively. Results from the three listening conditions, hearing aid (HA) alone, cochlear implant (CI) alone, and the combined devices (CI +HA), are represented by closed squares, closed circles, and open triangles, respectively.

Both the individual and average data show the same trend: the hearing aid alone produced essentially zero speech recognition across different SNRs [$F(4,16)=1.88$, $p>0.05$], while the cochlear implant alone and the combined devices produced monotonically increasing performance as a function of SNR [CI alone: $F(4,16)=10.98$, $p<0.01$; CI +HA: $F(4,16)=23.09$, $p<0.001$]. The most interesting finding is that the combined hearing produced significantly better performance than the CI alone particularly in the higher SNR conditions by an average of 8 percentage points at a 15 dB SNR [$F(1,4)=10.78$, $p<0.05$] and 20 percentage points at a 20 dB SNR [$F(1,4)=27.13$, $p<0.01$].

Figure 3 shows sentence recognition scores with the female masker from subjects S2, S3, and S4. Similar to the male masker condition, qualitative trends were observed with the female masker: (1) the HA alone produced essentially zero speech recognition, (2) both the CI alone and the combined devices produced monotonically increasing perfor-

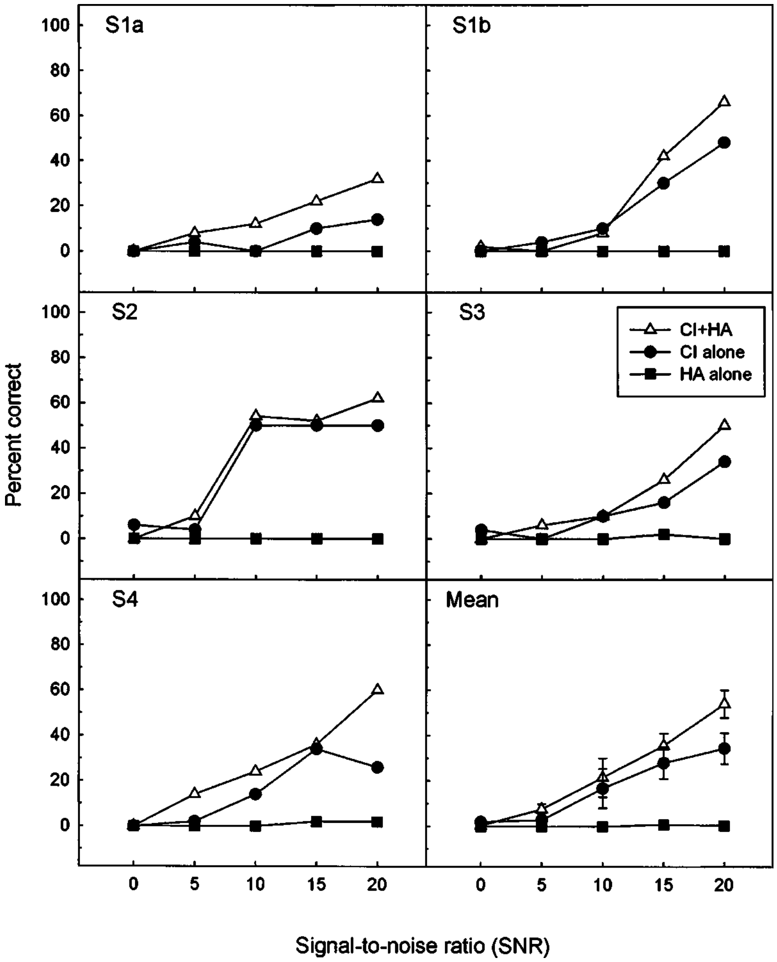

FIG. 2. Individual and mean sentence recognition scores (% correct) as a function of signal-to-noise ratio (SNR) with the male masker. The three functions in each panel represent the CI+HA (open triangles), CI alone (closed circles), and HA alone (closed squares) conditions. The vertical error bars in the mean graph represent the standard error of the mean.

mance as a function of SNR, and (3) the combined hearing produced better performance than either mode alone. The benefits of combined hearing compared to CI alone were observed in all subjects, with average improvement ranging from 8 to 25 percentage points from 0 to 20 dB SNR. However, due to the limited number of subjects and the large

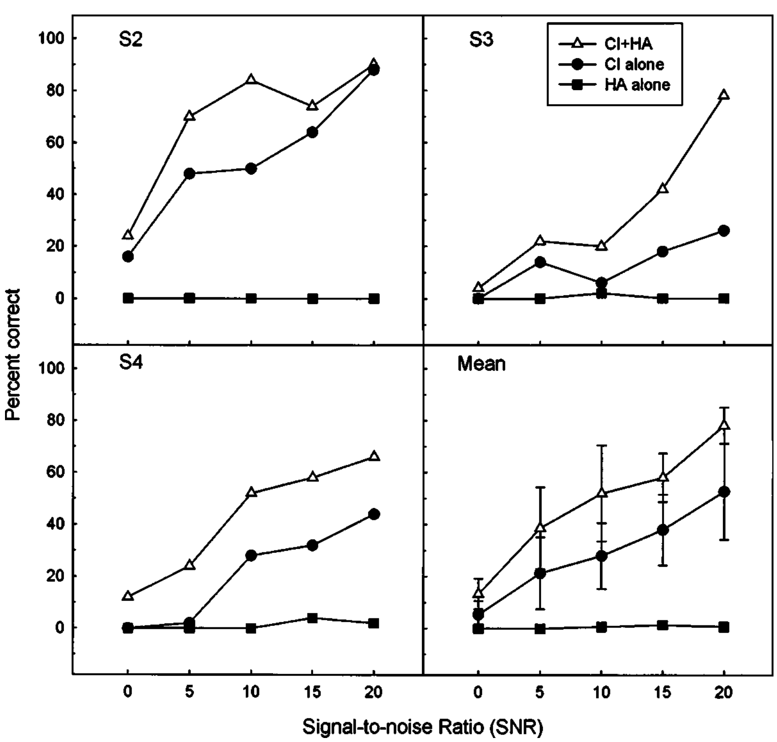

FIG. 3. Sentence recognition scores (% correct) as a function of SNR for subjects S2, S3, and S4 with the female masker.

intersubject variability of performance, the superior performance of combined hearing over CI alone was only found to be significant at 15 [$F(1,2)=19.10$, $p<0.05$] and 10 dB SNRs [$F(1,2)=18.75$, $p<0.05$]. Large differences between the male and the female maskers were observed in the combined hearing condition at all SNRs with an average of 21 percentage points better with the female masker than with the male masker. Significant difference between the two maskers in combined hearing was found in more challenging SNRs at 15 [$F(1,2)=100.00$, $p<0.01$] and 10 dB SNRs [$F(1,2)=19.24$, $p<0.05$]. In contrast, with the CI alone, the improvement of speech recognition with the female masker compared to the male masker was relatively small (average 9 percentage points) and no significant difference between maskers was found at any SNR [$F(1,2)=2.07$, $p>0.1$]. The improvement of the combined hearing over the CI alone was much greater for the female masker (average 19 percentage points) than the male masker (average 7 percentage points). For example, subject S2 improved by about 5 percentage points with the male masker, but the improvement with the female masker was 26 and 34 percentage points at 5 and 10 dB SNR, respectively. Similarly, subject S3 improved by 15 or less percentage points with the male masker, but the improvement with the female masker was 24 and 52 percentage points at 15 and 20 dB SNR, respectively.

III. MELODY RECOGNITION

A. Methods

1. Subjects

Five cochlear-implant subjects, including the same four cochlear-implant subjects from experiment I and an additional subject S5 participated in the melody recognition experiment. Only S1 had extensive musical training, while the rest had very limited music experience. Subject S5 was a non-native speaker of English, but he attended kindergarten in the United States at age 6. He reported learning all the melodies, except one, used in the experiment at a young age and was able to hum the tunes of these melodies. He was implanted with the Clarion precurved electrode and was using the SAS processing strategy. Like most of the subjects in this experiment, S5 continued to use his hearing aid on a daily basis. His average aided threshold for 125, 250, and 500 Hz was 45 dB HL.

2. Stimuli

Three sets of 12 familiar melodies, played by single notes, were generated using a software synthesizer (ReBirth RB-338, version 2.0.1). For each melody, rhythmic information was removed by using notes of the same duration (quarter notes with 350 ms in duration) with a silent period of 150 ms between notes. Therefore, pitch was the only available cue for melody recognition. Each melody consisted of 12–14 notes of its initial phrase. Three sets of the twelve melodies were generated in low-, mid-, and high-frequency ranges. In the low-frequency melody condition, all melodies were within a frequency range from 104 (G#2) to 261 Hz (C4), whereas the mid- (208 to 523 Hz) and high-range (414 to 1046 Hz) melodies were one and two octaves above the low-range melodies, respectively. The largest semitone difference between the highest and the lowest notes of the melody was 16 and the smallest difference was 7. Table II shows the titles of the melodies used in this experiment and the frequency components of each melody (for detailed information, see Kong *et al.*, 2004).

TABLE II. The 12 familiar melodies and their frequency ranges.

Melody[a]	Low range	Mid range	High range	Largest interval[b]	Int extent[c]
1	131–220 (C3-A3)	261–440 (C4-A4)	522–880 (C5-A5)	5th	9
2	122–184 (B2-F#3)	245–369 (B3-F#4)	490–738 (B4-F#5)	m3rd	7
3	110–174 (A2-F3)	220–348 (A3-F4)	440–696 (A4-F5)	4th	8
4	110–184 (A2-F#3)	220–369 (A3-F#4)	440–738 (A4-F#5)	6th	9
5	110–174 (A2-F3)	220–348 (A3-F4)	440–696 (A4-F5)	4th	7
6	131–196 (C3-G3)	261–392 (C4-G4)	522–784 (C5-G5)	m3rd	7
7	110–220 (A2-A3)	220–440 (A3-A4)	440–880 (A4-A5)	Octave	12
8	146–220 (D3-A3)	292–440 (D4-A4)	584–880 (D5-A5)	4th	7
9	131–196 (C3-G3)	261–392 (C4-G4)	522–784 (C5-G5)	5th	7
10	103–261 (G#2-C4)	207–523 (G#3-C5)	414–1046 (G#4-C6)	m6th	16
11	104–233 (G#2-A#3)	207–466 (G#3-A#4)	414–932 (G#4-A#5)	4th	14
12	110–184 (A2-F#3)	220–369 (A3-F#4)	440–738 (A4-F#5)	5th	9

[a]1=Twinkle, Twinkle, Little Star; 2=This Old Man; 3=She'll be Coming Round the Mountain; 4=Old MacDonald Had a Farm; 5=Lullaby, and Good Night; 6=Mary Had a Little Lamb; 7=Take Me Out to the Ball Game; 8=London Bridge is Falling Down; 9=Happy Birthday; 10=Star Spangled Banner; 11=Auld Lang Syne; 12=Yankee Doodle.
[b]Largest interval in melody (m=minor).
[c]Range in semitones between the highest and the lowest notes in the melodies.

3. Procedure

All subjects were tested in three listening conditions (HA alone, CI alone, and CI+HA) and three melody conditions (low, mid, and high) for a total of 9 conditions. For the HA alone and CI alone conditions, stimuli were presented at the subject's most comfortable level while they wore their hearing aid or cochlear implant at their usual settings. For the combined CI+HA condition, the presentation level was set the same as in the HA alone condition while the speech processor volume was adjusted to achieve the most comfortable loudness. The presentation level ranged from 70 to 85 dB SPL.

The titles of the 12 melodies were displayed on a computer screen and the subject was asked to choose the melody that was presented. A practice session with feedback was given before the actual test. For each experimental condition, melodies were presented three times in random order. Repetition of the stimulus was not allowed and visual feedback regarding the correct response was given immediately after

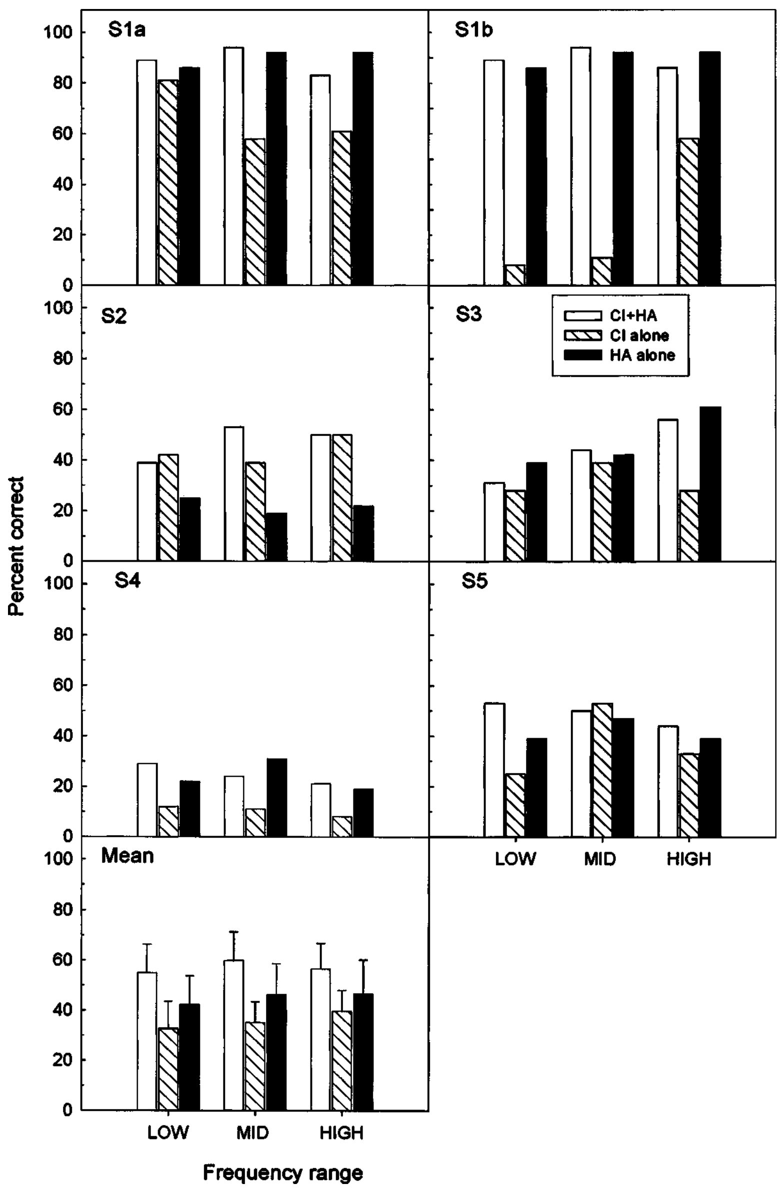

FIG. 4. Individual and mean melody recognition scores (% correct) for the three listening (CI alone, HA alone, and CI+HA) and three melody conditions (Low, Mid, and High). Vertical error bars represent the standard error of the mean.

the subject's response. As in experiment I, all three melody and all three listening conditions were presented in random order.

B. Results

Figure 4 shows individual and mean melody recognition results for the three melody (low, mid, and high) and listening conditions (HA alone=closed bars, CI alone=slanted bars, and CI+HA=open bars). Panels S1a and S1b represent results from subject S1 using the SAS and MPS strategies, respectively. Melody recognition performance varied remarkably from subject to subject in all listening conditions. Performance ranged from an average of 19% for S4 to 90% for S1 in the HA alone condition, from 8% for S4 to 81% for S1 in the CI alone condition, and from 21% for S4 to 92% for S1 in the CI+HA condition. Consistent with Kong *et al.* (2004), a difference in processing strategies was observed, with the SAS strategy producing better melody recognition than CIS-type strategy. For subject S1, her SAS strategy produced 73, 47, and 3 percentage points better performance than her MPS strategy for the low-, mid-, and high-range melodies, respectively. However, inconsistent with earlier studies on melody recognition, the melody recognition performance with cochlear implants alone in some of the subjects was considerably better than the chance performance level (e.g., Gfeller *et al.*, 2002; Kong *et al.*, 2004). It should be noted that the melody recognition performance with the mid-range melodies reported in Kong *et al.* (2004) was primarily obtained from cochlear implant users with the older devices (Clarion precurved and Nucleus-22) and with the envelope extraction processing strategies, namely MPS, CIS, and SPEAK. Preliminary data from our laboratory on a small group of users implanted with Nucleus 24, Clarion HiFocus II, and Med-El devices showed a different level of performance, with some performing similarly to the older device users at chance level and others in the range of 40%–80% correct. The reasons for this remarkable difference in performance between the newer and older devices will need further investigation, but it is not in the scope of discussion in this study.

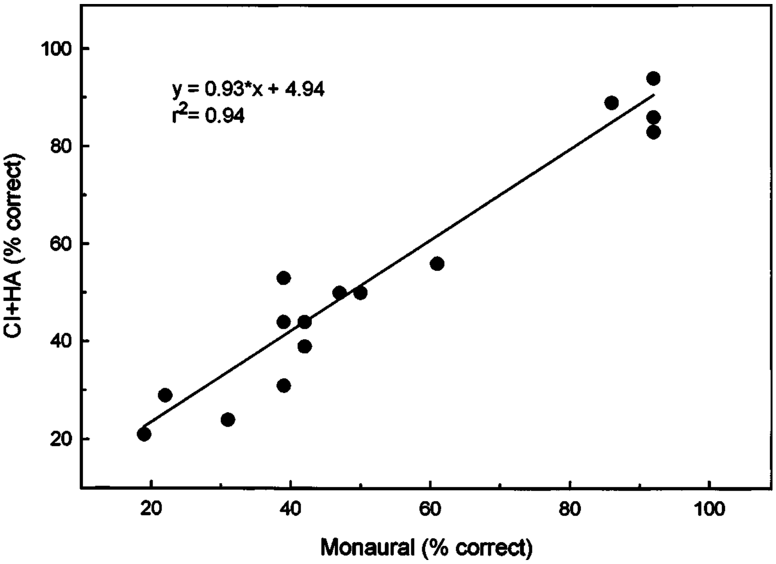

FIG. 5. Correlation of melody recognition (% correct) with binaural (CI+HA) and monaural (HA alone or CI alone) stimulation. Monaural data from S1a, S1b, S3, S4, and S5 are from the HA alone condition, but from the CI alone condition for S2. The slope of the regression line is 0.93 and the intercept is 4.94.

With the HA alone, the average melody recognition performance across all subjects and conditions was 45% correct. This is in direct contrast with the score of 0% obtained for the speech recognition in noise task from the first experiment. On average, HA alone produced an average of 17 percentage points better melody recognition than the averaged CI alone performance, but showed similar performance to the combined hearing condition. These patterns of results were observed in four out of the five subjects. The only exception was subject S2, who discontinued the regular use of his hearing aid after implantation and had very unusually poor aided thresholds in the frequency range (<1000 Hz) that was tested in this experiment. Due to the large intersubject differences in the melody recognition scores, a repeated measures ANOVA did not show significant difference between the HA alone and CI alone performance. Nevertheless, the trend of better performance with the HA alone than the CI alone was found in 14 out of the 18 cases, the probability of obtaining this result by chance is only 1.2%.

IV. DISCUSSION

A. Comparison between speech and melody recognition

Cochlear implant speech recognition performance in quiet has improved with advances in technology, but speech recognition in competing backgrounds and music perception remains challenging for implant users. One of the reasons for their poor performance in speech recognition in noise and music perception is their impaired pitch perception ability caused by both the limitations of the electrode design and the signal processing scheme employed in current cochlear implants. We hypothesize that providing the additional fine-structure information at low frequencies via the nonimplanted ear may allow for better encoding of pitch, which in turn can improve music appreciation and enhance speech recognition in competing backgrounds.

The present study showed that speech recognition in noise improved with combined acoustic and electric hearing compared to electric hearing alone, consistent with findings in earlier combined hearing studies (Armstrong *et al.*, 1997; Ching *et al.*, 2001 and 2004; Tyler *et al.*, 2002) and the results reported regarding "short-electrode" cochlear implants (Turner *et al.*, 2004). Turner *et al.* (2004) showed significantly lower spondee word reception thresholds in the presence of two simultaneously presented sentences than in steady-state white noise in "short-electrode" users, but not in the traditional long-electrode users. In contrast to speech recognition, the advantage of combined hearing was not observed in the melody recognition task. Instead, the performance with combined hearing was determined by the better ear (i.e., acoustic ear in S1, S3, S4, and S5, implant ear in S2), as indicated by Fig. 5 showing a highly significant correlation between the binaural and the best monaural conditions [$r^2=0.94$, $p<0.001$] and close to the unit slope (0.93) of the linear regression function.

The differential speech and music results reinforce the recently reported dichotomies in auditory perception, i.e., the fine-structure cue at low frequencies dominates pitch perception while the envelope cue dominates speech recognition (Smith *et al.*, 2002). The present results demonstrate this dichotomy with opposite patterns of results between hearing aid and cochlear implant performance in speech and melody recognition: the hearing aid (containing the fine-structure cue at low frequencies) produced no speech recognition but significant melody recognition, while the cochlear implant (containing the temporal envelope cue) produced significant speech recognition but relatively poor melody recognition. The inability to recognize speech with only low-frequency information is consistent with classic articulation index studies, where low-pass filtered speech (≲800 Hz) was relatively unintelligible (e.g., French and Steinberg, 1947; Pavlovic *et al.*, 1986). However, this additional low-frequency acoustic information, when combined with the cochlear implant, produced significantly better speech recognition in noise than the implant alone condition.

B. Auditory segregation and grouping

The superior speech recognition performance in binaurally combined hearing over the CI alone may arise from the benefits of (1) binaural processing including the binaural squelch effect (Carhart, 1965; Colburn, 1977) and/or diotic summation, a small benefit arising from listening with two ears compared to one ear with the identical signal and noise (Day *et al.*, 1988), (2) a monaurally based grouping and segregation mechanism, or (3) a combination of both. However, we argue that the presently observed improved speech recognition in noise with binaurally combined acoustic and electric hearing cannot be due to the binaural advantage. First, there are apparently no preserved level and phase differences between the acoustic and electric hearing, as required by the traditional binaural squelch. Both the target speech and masker were presented directly in front of the subjects in our study. Second, the advantage from diotic summation is small (Cox *et al.*, 1981) and it results mainly in better speech recognition in quiet (Kaplan and Pickett, 1981). This cannot account for the considerably large improvement of speech recognition in noise (averaged 19 percentage points with the female masker) with the combined hearing in our study. Third, similar improvement was obtained with combined acoustic and electric hearing on the same side with the short-electrode implant, providing evidence strongly against the binaural advantage hypothesis. Fourth, speech recognition in noise was improved more with the female masker than with the male masker, suggesting a monaurally based grouping and segregation mechanism.

Previous studies in which speech recognition in noise improved with the separation of the fundamental frequency have demonstrated the importance of voice pitch cues for segregating speech from competing backgrounds (e.g., Brokx and Nooteboom, 1982; Gardner *et al.*, 1989; Assmann and Summerfield, 1990). During voicing, the pulsing of the vocal folds gives rise to a consistent pattern of periodicity in the time wave form and corresponding harmonicity in the spectrum. Different from acoustic hearing, low harmonics cannot be resolved in current cochlear implants. The only pitch information available in the implants is from the reduced salience pitch cue provided by the temporal envelope (Burns and Viemeister, 1981; Faulkner *et al.*, 2000; Green *et al.*, 2002). The nonsalience of temporal envelope pitch can be demonstrated by the much poorer discriminability of modulation frequency and electric pulse rate than pure-tone frequency discrimination (Formby, 1985; Grant, 1998; Zeng, 2002). Thus, we hypothesize that the pitch difference in the temporal envelope is not robust enough to reliably separate the target and masker, particularly when both are dynamic speech sounds (e.g., Green *et al.*, 2002). We further hypothesize that the fine-structure information at low frequencies in the combined acoustic and electric hearing provides better $F0$ information that allows the cochlear-implant users to segregate the target from the masker. In the present study, the average fundamental frequency was 108 Hz for the target, 136 Hz for the male masker, and 219 Hz for the female masker (measured by the STRAIGHT program, courtesy of Kawahara, 1997). The significantly better speech recognition performance with the female masker compared to the male masker supported the idea that the availability of the fundamental frequency cue in combined acoustic and electric hearing was critical for separating the target speech from the masker speech.

The encoding of voice pitch in normal-hearing listeners can be achieved by the place coding or temporal coding mechanism, or both. A number of models have been proposed to investigate the auditory and perceptual processes by which normal-hearing listeners utilize the $F0$ difference when identifying the constituents of double vowels. Assmann and Summerfield (1990) tested different models to predict performance in normal-hearing listeners in identifying concurrent vowels with different fundamental frequencies. They reported that the place-time models, which estimated voice pitch using a periodicity analysis of the wave forms in each channel, were superior to the place models in the context of vowel identification. A purely temporal model by Meddis and Hewitt (1992) could even predict the improvement of segregation of simultaneous vowels as a function of $F0$ difference based on the pooled periodicity information which were summed across channels. These models suggested that temporal information, namely the periodicity cues, are critical for the segregation of competing sound sources.

The underlying mechanism for segregating competing sounds with combined acoustic and electric hearing is unclear. We propose that the segregation of target speech from the masker is based on the temporal periodicity cues in both the acoustic and electric signals. While the periodicity cue carried in the envelope alone does not provide sufficient $F0$ sensitivity to perceptually segregate target speech from the masker (Faulkner *et al.*, 2000; Green *et al.*, 2002), the presence of the additional salient temporal fine-structure cue at low frequencies in acoustic hearing, which is correlated with the periodicity cue in the temporal envelope in electric hearing, increases perceptual segregation between the signal and noise as well as improves grouping of the signal and that of the noise. This hypothesis is consistent with the recently reported poor (23% correct) speaker identification performance (Vongphoe and Zeng, 2004) and the absence of talker effect for speech recognition in the presence of a competing talker (Stickney *et al.*, 2004) in cochlear implant users. Even though there is no direct evidence to support this hypothesis at this stage, several predictions can be made to test its validity in the future. For example, should fundamental frequency be the main cue used by low-frequency acoustic hearing to improve electric hearing, we would predict minimal improvement for voiceless speech segments. Additionally, any mismatch between the fundamental frequency provided by acoustic hearing and the temporal envelope provided by electric hearing would result in a reduced benefit in combined hearing.

V. CONCLUSIONS

The present study implicates a dichotomy between the envelope and fine-structure cues at low frequencies in speech and melody recognition. The temporal envelope cue is sufficient for speech recognition, but not for melody recognition. On the other hand, the fine-structure cue at low frequencies is sufficient for pitch perception, but not for speech recognition. However, when the fine-structure cue in acoustic hearing is combined with the envelope cue in electric hearing, significant improvement can be observed in speech recognition in a competing background. The greatest improvement was observed when the target and the masker had the largest difference in fundamental frequency, suggesting a monaurally based grouping mechanism rather than a binaurally based mechanism for the observed advantage with the combined acoustic and electric hearing.

The present study suggests the importance of appropriately encoding the fine-structure cue in cochlear implants. Although this fine-structure cue at low frequencies produces negligible intelligibility for speech recognition in quiet, it is critical for music perception, speech recognition in noise, and other listening situations including speaker identification and sound source segregation.

ACKNOWLEDGMENTS

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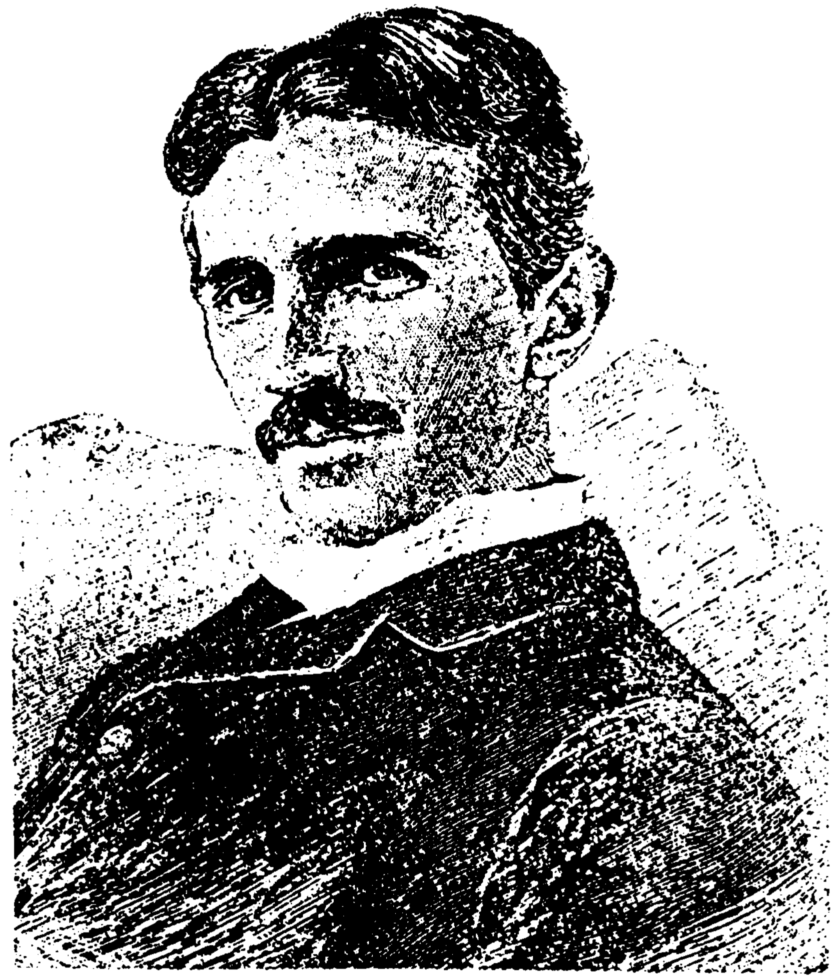
Tesla's "Self-Acting" Engine

by Peter A. Lindemann



IN June of the year 1900, Nikola Tesla published an article in **Century Magazine** titled *The Problems of Increasing Human Energy*. Never before or since has there been such a masterful and exhaustive discussion of how to extract useful energy from the environment. In its original magazine format, this article is 31 pages in length. After discussing every known method for energy generation then in use, Tesla begins a discussion of "a departure from known methods – possibility of a 'self-acting' engine – the ideal way of obtaining motive power".

Beginning on page 200, and continuing to page 204 of the original Century Magazine article, Tesla outlines his ideas. The following quotations are extracted from this section of the article.

"...a survey of the various ways of utilizing the energy of the medium convinced me, ..that to arrive at a practical solution, a radical departure from the methods then known had to be made. The windmill, the solar engine, the engine driven by terrestrial heat, had their limitations in the amount of power obtainable. Some new way had to be discovered which would enable us to get more energy."

"..the problem was to discover some new method which would make it possible both to utilize more of the heat-energy of the medium and also to draw it away from the same at a more rapid rate."

"I was vainly endeavoring to form an idea of how this might be accomplished, when I read some statements from Carnot and Lord Kelvin which meant virtually that it is impossible for an inanimate mechanism or *self-acting machine to cool a portion of the medium below the temperature of the surrounding, and operate by the heat extracted.* These statements interested me intensely. Evidently, a living being could do this very thing, and since the experiences of my early life...convinced me that a living being is only an automaton, or, otherwise stated, a 'self-acting engine,' I came to the conclusion that it was possible to construct a machine which would do the same."

"Suppose that an extremely low temperature could be maintained by some process in a given space; the surrounding medium would then be compelled to give off heat, which could be converted into mechanical or other form of energy, and utilized. By realizing such a plan, we should be enabled to get at any point of the globe a continuous supply of energy, day and night."

"A closer investigation of the principles involved, and calculation, now showed that the result I aimed at could not be reached in a practical manner by ordinary machinery, as I had in the beginning expected. This led me, as a next step, to the study of a type of engine generally designated as 'turbine,' which at first seemed to offer better chances for a realization of the idea."

"..my conclusions showed that if an engine of a peculiar kind could be brought to a high degree of perfection, the plan I had conceived was realizable, and I resolved to proceed with the development of such an engine, the primary object of which was to secure the greatest economy of transformation of heat into mechanical energy."

"(In early 1895) Dr. Carl Linde announced the liquefaction of air by a self-cooling process, demonstrating that it was practicable to proceed with the cooling until liquefaction of air took place. This was the only experimental proof which I was still wanting that energy was obtainable from the medium in the manner contemplated by me."

"Much of this task on which I have labored so long remains to be done. A number of mechanical details are still to be perfected and some difficulties of a different nature to be mastered, and I cannot hope to produce a self-acting machine deriving energy from the ambient medium for a long time yet, even if all my expectations should materialize."

Tesla's idea was radical. Design a machine powered by the heat resident in the ambient air that produced an output of mechanical energy and refrigeration simultaneously. He called it "the ideal way of obtaining motive power". Such a machine would be able to produce useful energy at any time of the day or night, at any location on the globe, drawing upon the vast heat reservoir of the atmosphere. He worked for years toward this goal and absolutely convinced himself, by the power of his own nearly infallible logic, of its potential reality.

To my knowledge, Tesla never finished the work on this invention. But his pioneering efforts clearly conceived the idea, as well as outlined most of the engineering problems to be solved.

It's remarkable to me, that with all of the attention given to Nikola Tesla in the last few years, I have not heard any mention of this aspect of his work. Volumes have been written on so-called "free energy" devices, wherein the would-be inventors are searching in vain for a ubiquitously present, inexhaustible source of energy from which their machines may draw. Imaginative theories have postulated "tachyons", "zero-points", and "magnetism" as the source of choice from which to extract energy. And, while future work may prove that these sources can be made practical, it is still surprising that the most readily available, untapped source of energy from which to draw, atmospheric heat, has been all but neglected.

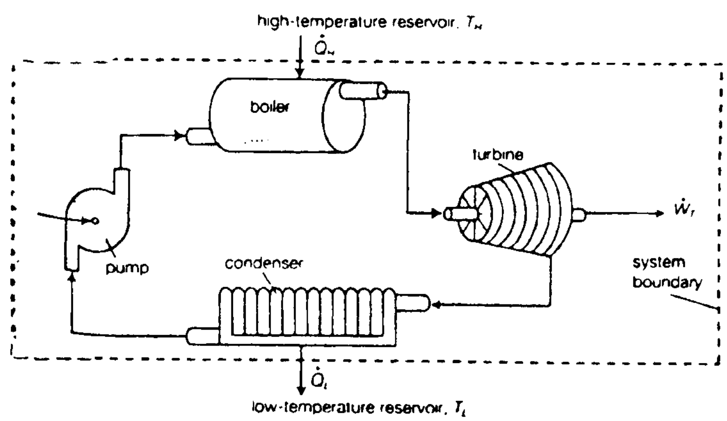


Figure 1 - Steam Engine

The patent office is crammed with hundreds of "permanent magnet motors", none of which work, to my knowledge. Tesla dismisses these ideas with a short stroke, "We may even find ways of applying forces such as magnetism or gravity for driving machinery without using any other means. Such realizations, while highly improbable, are not impossible." While leaving the door open, Tesla considers this area of research worthy of only a brief mention. He then goes on for four pages, discussing his efforts to tap the ambient temperature as a source of power.

Tesla was a master thinker and inventor. His mind penetrated the ultimate solution to humanity's energy needs. Like a scientific Sherlock Holmes using the power of his own deduction, when all of the "improbables" and "impossibles" were removed, what remained must be the solution. Atmospheric heat was the largest untapped reservoir of energy on the planet. Tesla refused to overlooked the obvious. He was that rare fish capable of contemplating the water he was swimming in. Few were able to follow his ideas. Even fewer were able to follow-up on his work

When I first read this article from **Century Magazine**, I was fascinated by the section on the "self-acting" engines. But Tesla's idea of gaining energy by dumping heat into an inexhaustible "cold spot" seemed unrealizable. My mind could not penetrate the unknowns involved. Luckily, other minds were not so dull.

To begin to get an understanding of Tesla's idea, let's first look at the fundamentals of fluid dynamics. Follow along if you can. If a gaseous fluid (like air) is confined in a closed space, three properties of this gas become interdependent upon each other. These properties are: 1) Volume, how much space it occupies, 2) Temperature, how much heat it contains, and 3) Pressure, how much force it exerts on the walls of the container. For instance, if the container remains the same size and we increase the temperature of the air inside, the pressure it exerts on the walls also rises. Likewise, if the volume stays the same and we reduce the pressure, the temperature must also drop. Conversely, if we increase the volume, either the temperature or the pressure will go down (or both). From this we may see that temperature and pressure are directly related to each other, but are inversely related to the volume. This is how Dr. Carl Linde liquefied air by his "self-cooling" process. By manipulating the pressure and volume of a quantity of gaseous air, he was able to liquefy some of it by taking advantage of these principles.

One hundred years ago, this was an amazing accomplishment. Now, these processes are used commercially every day. To illustrate, we need go no further than a useful novelty available in a mail order catalog. Many compressed gases are available today. One of them is carbon dioxide. For less than $30, you can buy a special nozzle that attaches to a canister of compressed carbon dioxide. When the gas is released through this nozzle, "dry ice" is formed. Room temperature compressed carbon dioxide, when allowed to expand rapidly under controlled conditions, refrigerates itself to form "dry ice". By this method, about 20% of the compressed gas can be liquefied, or in this case, solidified. This illustrates what Tesla refers to as the "self-cooling" process that allowed Dr. Carl Linde to liquefy air in 1895. Tesla immediately understood the implications. He states that his invention could be designed to run on liquid air, but that "its temperature is unnecessarily low." All that was needed was a working fluid that changed from a gas to a liquid at a temperature below the ambient.

Dr. Linde's process required a mechanical energy input to compress the air. But Tesla knew that mechanical processes were reversible. The machine he envisioned used the methods discovered by Dr. Linde, but ran them backwards. To understand how this can be done, we need go no further than our own medicine cabinet. If room temperature isopropyl alcohol is rubbed on your arm, it "feels cold". It feels cold because it is evaporating. It is evaporating because of a change in "vapor pressure" between the closed bottle and the open air. This change of pressure is "forcing" the evaporation to take place. But, for the alcohol to evaporate (change from a liquid to a gas), it needs heat. Since no heat source is available, it must get the necessary heat from the immediate environment. So, it extracts that heat from your arm. That's why your arm feels cold (refrigeration). Believe it or not, Tesla saw an energy machine in all of this. The one part of the equation that is not so apparent here, is that the volume of space occupied by the evaporating alcohol is increasing dramatically. This increasing volume of gas could be confined to form a pressure that could drive an engine. Tesla saw it all, and knew what it meant. He spent years trying to solve all of the engineering problems associated with it, so that a future society could have all of its energy needs supplied by these processes.

So, what does Tesla's "self-acting" engine really look like? In order to visualize this, it may be helpful first to review the workings of two different kinds of heat systems that operate on "two phase fluids"; the first is a steam engine and the second is a heat pump. In Figure 1, water is boiled in the boiler to become pressurized steam. This high temperature, high pressure steam is then used to drive a turbine engine to convert the vapor pressure into mechanical work. The low temperature, low pressure steam coming out of the turbine is then allowed to cool further in the condenser, becoming liquid water again. The liquid water is then pumped back into the boiler, and the cycle begins again. In this example, we can easily see that the system takes in heat at the boiler and gives off heat at the condenser.

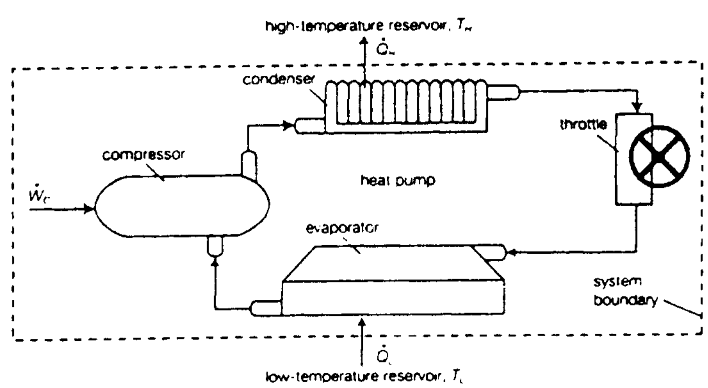


Figure 2 - Heat Pump

Figure 2 is a diagram of a heat pump. Low temperature vapor enters the compressor and is compressed to a high pressure and temperature. This vapor is then condensed to a liquid in the condenser. Then, the pressurized liquid is throttled through a special nozzle to low pressure and temperature. Releasing the pressure allows some of the liquid to vaporize. This "two phase fluid", part liquid and part vapor, now enters the evaporator, in which the remaining liquid is boiled. The resultant low temperature vapor then enters the compressor, completing the cycle. In this example, we can see that the system takes in heat at the evaporator and gives off heat at the condenser.

There is a high degree of similarity between these two systems. Both have a location where heat is absorbed (boiler and evaporator). Both have a location where the pressure is released (turbine and throttle). Both have a location where heat is released (condensers). And both have a location where the working fluid is pressurized to complete the cycle (pump and compressor). In the steam engine, heat energy is added to the system at the boiler and mechanical energy is removed from the system at the turbine. That amount of heat that was not successfully transformed to mechanical energy at the turbine, is then thrown away at the condenser and represents a loss of efficiency. In the heat pump, mechanical energy is added to the system at the compressor and heat energy is removed from the system at the condenser. That amount of liquid that vaporizes at the throttle represents a loss of efficiency because no heat is absorbed from the environment to create the vaporization.

The main difference between these two systems is that the steam engine runs on a working fluid (water) that changes phase from a liquid to a gas at 212° Fahrenheit, whereas the heat pump runs on a working fluid (freon) that changes phase from a liquid to a gas at -50° Fahrenheit. Tesla's "self-acting" engine was a unique hybrid between these two systems.

Tesla knew that his system, if it was to work, had to be much more efficient than standard systems. In our steam engine example, for instance, if we could eliminate the condenser, the system would be more efficient. In our heat pump example, if we integrated the throttle into the evaporator so that all of the expansion happened there, the system would be more efficient. These are the kinds of engineering problems Tesla was attempting to solve.

By taking elements from both of these systems, we can begin to understand what Tesla had discovered. Figure 3 shows such a system. It runs on a low temperature phase change material, like freon. The first element acts like a combination of the pump and the compressor. Its job is to take the "two phase fluid", part liquid and part vapor, and compress it until it is 100% liquid. The next element of the system takes the place of the boiler. It is really a heat exchanger that allows the working fluid to absorb heat from the environment *without* boiling. On the outside, this element gets cold and produces refrigeration effects. On the inside, the working fluid is gaining in its stored heat potential. The next element of the system is the throttle or control valve. This component allows the pressurized, liquid material to experience a rapid pressure drop that promotes instant vaporization of *some* of the working fluid. Since no heat source is available here, the heat of vaporization must come from the stored heat in the working fluid itself. This rapidly expanding vapor/liquid combination is then harnessed by the next element of the system, the turbine. As Tesla said, this is "an engine of a peculiar kind." It must be able to efficiently operate on the part vapor, part liquid material coming through it. When the volumetric expansion is spent, the "two phase fluid" is then re-compressed to a liquid, and the cycle starts over. Tesla envisioned that his turbine would produce more mechanical energy than the compressor required, so that the system would produce a net gain of mechanical energy.

Unlike the two previously discussed systems, Tesla's "self-acting" engine has no condenser where unused heat is thrown away. Heat energy is absorbed from the ambient, mechanical energy is removed from the turbine and all of the remaining heat potential in the working fluid is recycled for the next go-round.

The whole thing is an amazing idea, but will it work? Can the necessary efficiencies actually be attained? In the 1930's, an Austrian engineer named Rudolf Doczekal successfully built a steam engine that ran on a combination of water and benzene. To his amazement, it could run with or without the condenser in the system. Its efficiency was well above the calculated Carnot Cycle maximum. He was granted a Patent on this system in 1939 (NR. 155744). It took 39 years, and someone else to prove it, but Tesla was right; a high efficiency heat engine could be run without a condenser.

But can all of the other efficiencies be attained? Is there a device that can efficiently compress the "two phase fluid" back to a liquid? The answer is yes. Today, the Copeland Scroll Compressor can perform this function. Is there a turbine that can run efficiently on the rapidly expanding "two phase fluid?" Again, the answer is yes. Impulse turbines with the pressure nozzles built directly into the housing can perform this function, so that all of the fluid expansion occurs inside the engine. In fact, all of the other engineering problems have been solved.

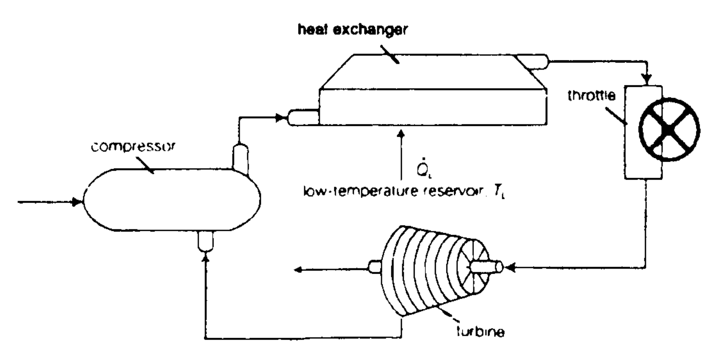


Figure 3 - Tesla's "Self-Acting" Engine

Today there are working models of machines that convert the ambient temperature of the air into mechanical energy, while creating refrigeration as a by-product. One hundred years after Tesla identified the "ideal way of gaining motive power", the gigantic reservoir of atmospheric heat has been successfully tapped. Real "free energy" has arrived on planet Earth. Obviously, the working details of these machines are complicated. The average reader will not have a thorough understanding of them without considerable study. Still, the basic principles upon which they operate have been outlined here with only minor over-simplification.

As of June, 1995, there are two slightly different processes being pursued that give the same basic result. The first is a machine designed by a German physicist, Dr. Bernhard Schaeffer, along with a Russian inventor, Albert Serogodski, building on the pioneering work of Doczekal. Their latest machine has been granted German Patent # DE 42 44 016 A 1, and is capable of being embodied as a refrigerator that produces electricity rather than consumes it. The other development is based on the work of Canadian engineer, George Wiseman, building more directly on Tesla's ideas. Wiseman has written three books that fully outline the principles of this amazing invention. His **HEAT Technology Series, Book 1, Book 2,** and **Book 3** are must reading for anyone interested in this subject. In these books, turbine designs are explored along with complete mathematical models of the system. For copies of these books, write to: Eagle Research, Box 145, Eastport, ID, 83826 USA. Each book is $15, post paid in North America. Add $5 more for over-seas postage. Buy both books, as they cover different aspects of the system.

One hundred years ago, Nikola Tesla discovered the ultimate way to harness the energy of the sun by converting the ambient temperature of the air into mechanical energy. He outlined the entire method and even solved many of the difficulties himself. But forces during his lifetime prevented him from completing this work. His "self-acting" engine is a true fuel-less power plant, capable of producing useful energy at any location on the planet, at any time of the day or night. It has taken one hundred years for others to finally complete this work, but that day has now arrived. While I do not wish to minimize the irreplaceable and outstanding contributions by Wiseman, Schaeffer, Doczekal and others, still, it is to Tesla that the future owes its thanks once again.

When Tesla first conceived of this invention, he started by deciding that the basic assumptions embodied in the "Second Law of Thermodynamics" were not universally true and therefore could not act as an absolute limiting case. These assumptions are built into our lives today by the idea that if I want the temperature of my environment to be either warmer or cooler than the ambient, I have to expend energy to do it. Tesla was not afraid to question or even disagree with these assumptions. Even the stature and historic "authority" of Sadi Carnot and Lord Kelvin, whose work was the basis of the "Laws of Thermodynamics", did not intimidate him. He was willing to rethink all of the fundamentals in the light of his own experiments and insight, and draw his own conclusions. By doing so, he was able to conceive of an invention that has taken 100 years to create. ■

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