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The acoustic and perceptual cues affecting melody segregation for listeners with a cochlear implant

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Our ability to listen selectively to single sound sources in complex auditory environments is termed “auditory stream segregation.” This ability is affected by peripheral disorders such as hearing loss, as well as plasticity in central processing such as occurs with musical training. Brain plasticity induced by musical training can enhance the ability to segregate sound, leading to improvements in a variety of auditory abilities. The melody segregation ability of 12 cochlear-implant recipients was tested using a new method to determine the perceptual distance needed to segregate a simple 4-note melody from a background of interleaved random-pitch distractor notes. In experiment 1, participants rated the difficulty of segregating the melody from distractor notes. Four physical properties of the distractor notes were changed. In experiment 2, listeners were asked to rate the dissimilarity between melody patterns whose notes differed on the four physical properties simultaneously. Multidimensional scaling analysis transformed the dissimilarity ratings into perceptual distances. Regression between physical and perceptual cues then derived the minimal perceptual distance needed to segregate the melody. The most efficient streaming cue for CI users was loudness. For the normal hearing listeners without musical backgrounds, a greater difference on the perceptual dimension correlated to the temporal envelope is needed for stream segregation in CI users. No differences in streaming efficiency were found between the perceptual dimensions linked to the F0 and the spectral envelope. Combined with our previous results in normally-hearing musicians and non-musicians, the results show that differences in training as well as differences in peripheral auditory processing (hearing impairment and the use of a hearing device) influences the way that listeners use different acoustic cues for segregating interleaved musical streams.

Keywords: auditory streaming, cochlear implant, music training, melody segregation, hearing impairment, pitch, loudness, timbre

INTRODUCTION

The perception and enjoyment of music engages complex brain networks (Zatorre et al., 2007) and recent evidence highlights the importance of top-down processes as well as stimulus-driven processes (Tervaniemi et al., 2009; Strait et al., 2010). Music practice has been shown to induce changes in the structure and function of the brain pathways that process sound and leads to improved performance on perceptual tasks (for example Musacchia et al., 2007). However, other uncontrolled individual differences between the musicians and non-musicians may have also contributed to the differences found in musical aptitude (see Corrigan et al., 2013 and other papers from this special edition). In this study, we sought to resolve some of these issues by removing the training difference between groups, and comparing results from groups that differ in their peripheral processing of sound. Two experiments will compare the ability to segregate auditory streams between a group of cochlear implant users and a group of normal hearing listeners.

In a typical auditory streaming experiment (Bregman, 1990), listeners are exposed to a sequence of alternating high and low

notes—the sounds may be grouped together and perceived as coming from a single source (termed fusion), or perceived as streams from separate sources (termed fission). In the fusion case, the single stream is perceived as a “gallop.” In the fission case, the sequence will be perceived as two separate streams, or as a “Morse code.” The mechanism of auditory streaming and the part of the auditory pathway involved are still unclear. However, some evidence has shown peripheral cochlear (Hartmann and Johnson, 1991) and central cortical components (Carlyon, 2004). The “Peripheral Channeling” theory suggests that streaming depends primarily on the amount of overlap in the excitation pattern on the basilar membrane induced by the two stimuli; the more the two stimulus excitation patterns overlap, the more likely they are to be perceived as a single stream. A hearing impairment can affect the basilar membrane mechanisms and increases the region of excitation along the basilar membrane. Furthermore, the spread of current in a cochlear implant (CI) causes the stimulation of a wide area around each electrode. Therefore, according to the “Peripheral Channeling” theory, hearing impaired listeners should show a reduced ability to stream.

115 Recently many studies have highlighted the importance of the
 116 role of central processing in auditory streaming (for a review see
 117 Carlyon, 2004). This effect can be shown by studying differences
 118 caused by musical training. Marozeau et al. (2010) developed
 119 a new method to determine the perceptual distance needed to
 120 segregate a simple 4-note melody from a background of inter-
 121 leaved distractor notes. Results showed that for participants with
 122 musical training, the sound intensity was the most efficient cue.
 123 Compared with the spectral and temporal envelopes, only a small
 124 difference in intensity allowed a given level of melody segregation.
 125 For the non-musicians however, both intensity and spectral envelope
 126 were equally efficient streaming cues. How the acoustic cues
 127 and their perceptual correlates relate to streaming ability in CI
 128 users is currently unknown. Therefore, this study aims to examine
 129 the effects of the CI on a variety of the acoustic and perceptual
 130 cues responsible for streaming.

131 While CI users generally understand speech well in quiet envi-
 132 ronments, much improvement is needed for non-speech sounds
 133 such as music (for a review see McDermott, 2011), although
 134 there are some cases of CI users with good musical abilities,
 135 often associated with extensive musical training (Maarefvand
 136 et al., 2013). Unsatisfactory music perception with CIs is related
 137 to degradations in three underlying abilities: pitch discrimi-
 138 nation, timbre discrimination, and auditory streaming ability.
 139 Unfortunately, the use of a CI degrades the acoustic cues that
 140 give rise to perceptual differences between sound sources, thus
 141 reducing the ability of the CI user to segregate different sound
 142 sources. This in turn reduces the ability to separately hear multi-
 143 ple lines of melody and different instruments, as well as different
 144 voices among many. In these experiments, we used a stream-
 145 ing task in conjunction with multidimensional scaling techni-
 146 ques to characterize a common perceptual distance between
 147 streams, and thus could examine streaming ability separately
 148 to the streaming difficulties caused by the degraded auditory
 149 input.

150 The current study is divided into two experiments. In
 151 Experiment 1, listeners were asked to continuously rate the dif-
 152 ficulty of segregating a repeating 4-note target melody inter-
 153 leaved with pseudo-random distractor notes. The melody notes
 154 were always constant and repeated continuously throughout
 155 the experiment, while the distractor notes gradually changed
 156 in fundamental frequency range, intensity, temporal envelope
 157 and spectral envelope. The aim of the Experiment 1 was to
 158 determine the effect of various acoustic cues on the difficulty
 159 of segregating a melody from interleaved distractor notes. In
 160 Experiment 2, a discrete pair of melodies which differed on a
 161 combination of fundamental frequency range, intensity, tempo-
 162 ral envelope and spectral envelope simultaneously was presented
 163 on each trial. Listeners were asked to rate the similarity between
 164 two melodies. This experiment provided a measure of the per-
 165 ceptual salience of each acoustic cue. While the first experi-
 166 ment's results are in terms of acoustic cue differences between
 167 streams, the results from the second experiment allow these dif-
 168 ferences to be re-cast in terms of perceptual differences. Taken
 169 together, the results of both experiments indicate the relationship
 170 between a perceptual difference and its ability to induce melody
 171 segregation.

EXPERIMENT 1

172 Experiment 1 with CI users aimed to determine how the difficulty
 173 of segregating a repeating 4-note melody from a background of
 174 random distracter notes was affected by changes in the intensity,
 175 temporal envelope, spectral envelope, and fundamental frequency
 176 range of the background notes. This experiment is a replication of
 177 our previous study in normally-hearing listeners (Marozeau et al.,
 178 2010, 2013; Innes-Brown et al., 2011)¹.

PARTICIPANTS

181 A total of 12 CI recipients participated. **Table 1** lists demo-
 182 graphic and hearing-related information for all participants. All
 183 but one are native English speakers. Recruitment was conducted
 184 through the Cochlear Implant Clinic at the Royal Victorian Eye
 185 and Ear Hospital. All the participants gave written informed
 186 consent and were compensated for their travel expenses. This
 187 project conformed to The Code of Ethics of the World Medical
 188 Association (Declaration of Helsinki), and was approved by the
 189 Royal Victorian Eye and Ear Hospital Human Research Ethics
 190 Committee (Project 10-995H).

STIMULI

193 All stimuli were 10-harmonic tones with random phase generated
 194 in Matlab 7.5 through simple additive synthesis. In Experiment
 195 1 the procedure was controlled using MAX/MSP 5 and stimuli
 196 were played back through a soundcard (M-AUDIO ProFire 610)
 197 and loudspeaker (Genelec 8020APM) positioned on a stand at the
 198 listener's ear height, 1 m from the participant's head.

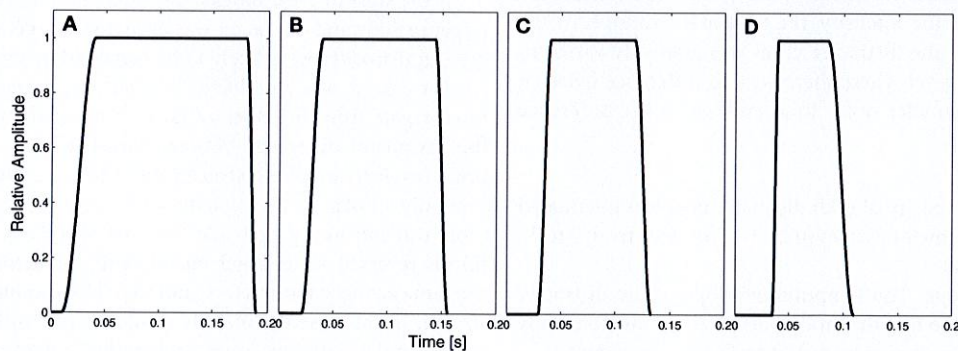
199 The target melody was a 4-note repeating pattern with the
 200 following acoustic parameters:

- 201 1) The F0 sequence was G4-C5-A4-D5, or midnote 67–72
 202 69 and 74. For convenience, the F0 will be represented in
 203 midnote, where each semitone is coded by consecutive inte-
 204 gers (middle C is 60). The intervals in the sequence were
 205 chosen to be sufficiently large to allow CI recipients to dis-
 206 criminate between adjacent notes while also being small
 207 enough for the notes to be grouped into a single stream.
 208
- 209 2) The temporal envelope (impulsiveness) of each note was com-
 210 posed of a 30-ms raised-cosine ramp on, a 140-ms sustained
 211 part, and a 10-ms raised-cosine ramp off for a total duration
 212 of 180 ms or an impulsiveness of 160 ms, defined as the full
 213 duration of the sound at half of the maximum amplitude (see
 214 **Figure 1A**).
 215
- 216 3) Intensity: As impulsiveness affects loudness perception, we
 217 varied the amplitude according to a temporal loudness model
 218 (Glasberg and Moore, 2002; ANSI, 2007). Intensity was var-
 219 ied so that sounds with different impulsiveness were presented
 220 at the same predicted loudness. The loudness of each melody
 221 note was 65 phons (as loud as a 1-kHz tone at 65 dB SPL) in
 222 free field according to the model.
 223
- 224 4) The spectral envelope of the notes consisted of 10 harmonics,
 225 successively attenuated by 3 dB (see **Figure 2A**).

226 ¹A portion of the data in the fundamental frequency condition has already
 227 been published (Innes-Brown et al., 2011). However, the data were analyzed
 228 differently in this paper.

229 **Table 1 | Summary of participant information.**

230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262
ID	Rating	MDS task	AGE	Sex	Years with	Implant	Etiology	Music training																								
codes	task	task	(years)		implant																											
N1	1	1	69.9	Male	7.9	Nucleus CI24R CA	Flu—infection	No																								
N2	2		62.3	Female	9.3	Nucleus CI24R CA	Hearing loss from childhood, hereditary/unknown	No																								
N3	3	2	62.3	Male	17.3	Nucleus CI22M	Meningitis	No																								
N4	4		76.2	Female	9.2	Nucleus CI24M	Hereditary	No																								
N5	5		90.2	Female	12.2	Nucleus CI24M	Unknown—gradual hearing loss	No																								
N6	6	3	75.6	Male	6.6	Nucleus CI24RE CA	Gradual HL from age 50	No																								
N7	7		72.7	Male	6.7	Nucleus CI24RE CA	Hereditary	No																								
N8	8		73.1	Male	13.1	Nucleus CI24M	Meniers Disease	No																								
N9	9		60.8	Male	17.8	Nucleus CI24M	Hereditary/unknown	No																								
N10	10		71.7	Female	10.7	Nucleus CI24R CS	Unknown, gradual loss over 7 years	No																								
N11	11		64.2	Female	9.2	Nucleus CI24R CS	Hereditary nerve deafness	No																								
N12	12		81.7	Female	13.7	Nucleus 24	Hereditary hearing loss—unknown	No																								
N13		4	74.4	Male	11.4	Nucleus Ci24	Familial—progressive postlingual deafness	No																								
N14		5	69.3	Male	4.3	freedom CA	Unknown	No																								
N15		6	46.5	Female	7.5	Freedom CA		No																								
N16		7	35.7	Female	3.7	Freedom CA	Pre-natal—unknown hereditary	No																								
N17		8	82	Female	4	Nucleus Ci24	Ototoxic antibiotics	No																								
Totals/Means	N = 12	N = 8	68.74 (13.1)	F = 9, M = 8	9.68 (4.2)																											



263 **FIGURE 1 | Temporal envelope of the stimuli for different level of impulsiveness: (A) 160 ms (ratio of distractor to target impulsiveness of 100%), (B)**
 264 **119 ms (ratio: 74%), (C) 90 ms (ratio: 56%), and (D) 60 ms (ratio: 37.5%).**

279 **PROCEDURE**

280 Because auditory streaming is affected by attention and other
 281 top-down influences, the choice of task and the directions used
 282 are important. In this experiment, we were interested in the
 283 minimum perceptual difference between streams which would
 284 allow participants to segregate the two streams (for a review
 285

see Bregman, 1990). Therefore, the participants attention was
 directed toward segregation (“finding” the melody). It is also
 important to take into consideration phenomena such as the
 “build-up effect,” in which listeners tend to initially group signals
 into the same stream, with segregation slowly appearing over the
 first few repetitions.

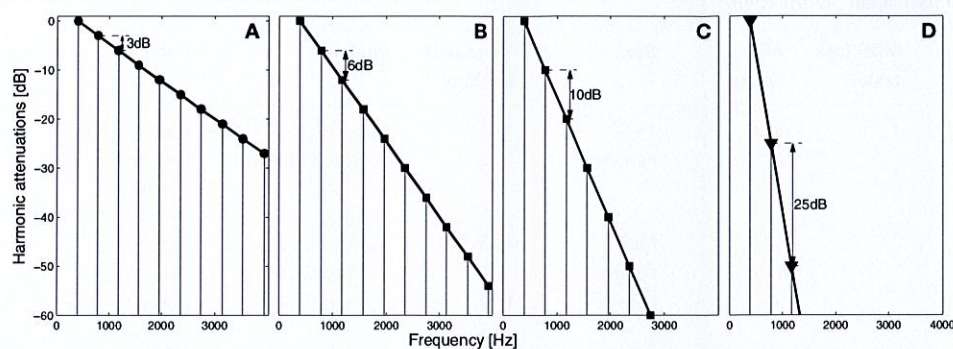


FIGURE 2 | Spectral envelope of the stimuli for different level: (A) 3 dB/harmonic (same attenuation than target melody), (B) 6 dB/harmonic (3 dB additional compared to the attenuation of target stimuli), (C) 10 dB/harmonic (7 dB additional), and (D) 25 dB/harmonic (22 dB additional).

The procedure used in this experiment generates a subjective measure of streaming and has been previously validated using a control experiment based on an objective detection task (Marozeau et al., 2010). During the experiment, participants continuously rated the difficulty of perceiving the target melody interleaved with pseudo-random pitch distractor notes using a slider on a midi controller (EDIROL U33, Roland Systems Group, Dee Why, NSW, Australia). The slider was labeled from 0 (no difficulty hearing the melody) to 10 (impossible to hear the melody). Participants were instructed to move the slider to the “10” position if the target melody was impossible to perceive, and to the “0” position if the target melody could be easily perceived. Ratings were re-scaled from 0–1 for analysis.

The acoustic properties of the melody notes were fixed throughout the experimental block, while a single acoustic property of the distractor notes was gradually changed. There were four conditions. In each of the conditions, either the fundamental frequency range, the intensity, the temporal envelope, or the spectral envelope of the distractor notes was gradually varied in 20 steps between a level where there was no difference between the melody and distractor notes to a level where the difference was pronounced.

- 1) Intensity. The intensity of each distractor note was attenuated compared to the melody notes in 20 2-phon steps from 0 to 38 phon attenuation.
- 2) Temporal envelope. The temporal envelope of the distractor notes was varied so that the ratio of distractor to target melody temporal envelope varied from 100 to 37.5% (see Figure 1).
- 3) Spectral envelope. The amplitude of each harmonic of the distractor notes was gradually decreased by the same amount in dB ranging in 20 logarithmically-spaced steps between 3 and 25 dB attenuation per harmonic (see Figure 2). In the text following the spectral envelope of the distractor notes is labeled as “additional attenuation per harmonic, ranging from 0 to 22 dB/harmonic relative to the target melody (static at 3 dB/harmonic).
- 4) Fundamental frequency. The 12-semitone F0 range of the possible distractor notes was gradually varied in 20 1-semitone steps from a range that totally overlapped the F0 range of

the target melody to at least one octave separation between the highest distractor note and the lowest target melody note. The F0 of each distractor note was chosen randomly from this range.

The experiment consisted of blocks of trials in which the target melody was repeated continuously while a single acoustic parameter of the distractor notes was gradually varied. In order to reduce possible pitch memory effects between blocks, a pitch increment, randomly chosen for each block between 0 and 4 semitones, was added to all notes in the block. The distractor notes either started with the parameter set at the level causing the most perceptual difference from the target melody and the difference decreased (DEC blocks), or began with the target melody and distractor sharing the same physical parameters and the difference increased (INC blocks).

At the start of DEC blocks, the perceptual difference between target melody and distractor was likely to be large, and so the target and distractor were likely to be perceived in separate streams. In this case it was also likely that the target melody was easy to segregate from the distractors, with low difficulty ratings. As the parameter difference between target melody and distractor began to decrease, the distractor notes became increasingly perceptually similar to the melody, and hence the melody became more difficult to segregate. At the start of INC blocks the situation is reversed—the target melody and distractor notes shared the same acoustic parameters, and were likely to fuse into a single stream. In this case the melody would be very difficult to segregate from the distractor notes, and gradually become easier as the experiment progressed.

After every 10 presentations of the target melody (16 s), the parameter level of the distractor was either increased (INC block) or decreased (DEC block). The block ended when the parameter reached either level 19 (in INC blocks) or 0 (in DEC blocks). A paradigm where the parameter step was gradually changed was preferred over a completely randomized design in order to avoid resetting the “buildup effect” (Carlyon et al., 2001) randomly, which would occur if the parameter step were varied significantly from one trial to the next. A DEC block was always run first as a practice session, with the data from this block discarded.

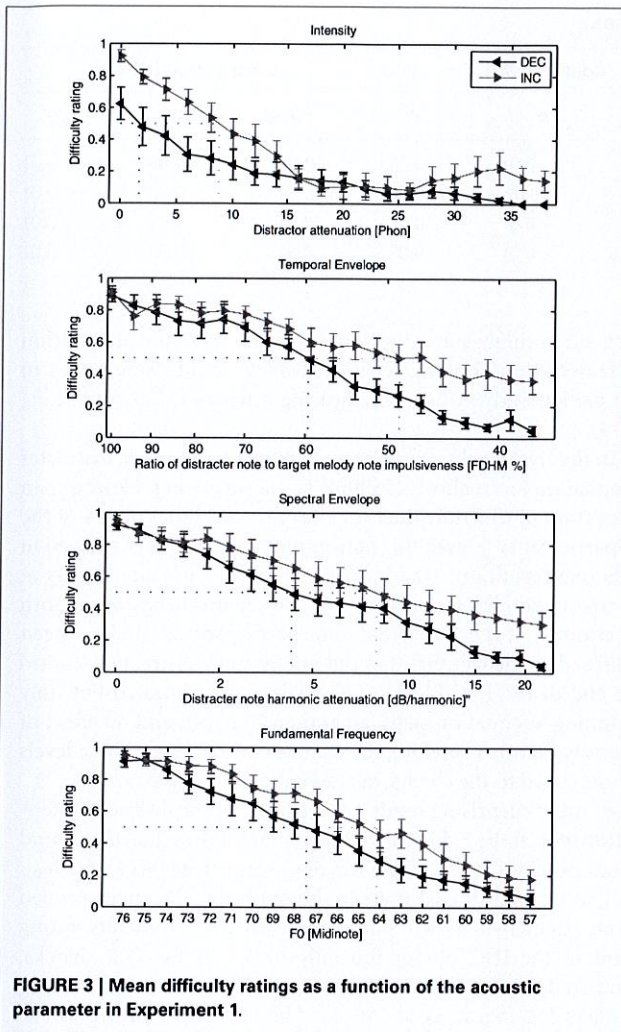


FIGURE 3 | Mean difficulty ratings as a function of the acoustic parameter in Experiment 1.

Following the practice session, INC and DEC blocks were run twice each, with A-B-B-A/B-A-A-B order counterbalanced across participants.

RESULTS

Figure 3 shows mean difficulty ratings as a function of the parameter level in each of the four conditions averaged across the participants and repetitions. For all conditions there was a quasi-monotonic relationship between the mean difficulty ratings and the parameter level (except in the intensity INC condition for the attenuations above 25 phons). As the physical difference between the target and the distractor increased, listeners on average reported less difficulty segregating the melody from distracter notes.

In order to test the statistical significance of each acoustic parameter on the difficulty ratings, a generalized linear model (GLM) was used. All statistical analysis was conducted using R version 2.15. A GLM was performed in each condition separately using the difficulty ratings as the dependent variable. A GLM was preferred over ANOVA because it is a mixed model with

categorical and continuous factors. The factor that was expected to have the most effect on the difficulty ratings was the physical difference between the target and the distractor. This factor will be called “Step” to reinforce the fact that the physical difference between the repeating melody and random distracter notes was varied with 20 intermediate steps ranging from similar (step 0) to very different (step 19). After visual inspection of the results (Figure 3) it was decided that a linear regression was appropriate to model the effect of the Step factor. Therefore, only one degree of freedom was needed. The other factors in the GLM were Context ($df = 1$, INC or DEC) and Repetition ($df = 1$, first or second repeat). The alpha level was set at 0.1. The results of the GLM are shown in Table 2.

In all four analyses, neither the main effect of Repetition nor any of its interactions was ever significant. This attests to the reliability of the method as difficulty ratings did not vary from block to block. The main effect of Step was highly significant and accounted for the highest proportion of the variability of the data. The main effect of Context was highly significant in three of the conditions, however only a trend was found in the Spectral condition. This is contrary to our previous findings in normally-hearing listeners, in which the Context (INC or DEC blocks) did not affect the difficulty ratings (Marozeau et al., 2013). As hearing ability decreases it is possible that previous knowledge of the sound is more important. No interactions were found between any factors. In order to further illustrate the effect of the INC or DEC context, we used linear interpolation to estimate the magnitude of each acoustic parameter that was present when the difficulty rating was 0.5 (fine dashed lines in Figure 3), separately in the INC and DEC conditions. In the DEC blocks, the experiment started with a large separation between the melody and distracter notes, and so difficulty ratings generally started low and increased toward the 0.5 point, whereas in INC blocks the situation was reversed. In the Intensity condition, an average of 8.7 phons difference between the target melody and distracter notes was needed for the participants to indicate a difficulty of 0.5 in INC blocks, and only 1.7 phons in the DEC blocks. In the Temporal Envelope condition, the distracter impulsiveness at the 0.5 difficulty rating point was less than half (48.9%) of the target melody impulsiveness in the INC blocks, and 59.5% of the target melody impulsiveness in the DEC blocks. In the Spectral Envelope condition, each successive harmonic was attenuated by an additional 8 dB/harmonic over the target melody in the INC blocks and an additional 4.3 dB/harmonic in the DEC blocks. In the F0 condition, the distracter ranged between midinote 64–56 in the INC blocks and between 67 and 58 in the DEC blocks. Overall, at the 0.5 difficulty rating point the distracter and target melody notes were much closer in each acoustic parameter when the task started easily and was gradually getting more difficult than vice versa.

DISCUSSION

The effect of intensity

The results in the intensity condition showed that the attenuation of the distracter notes had a large and significant effect on the difficulty ratings, and that the pattern of this effect was different according to the context (between the INC and DEC blocks). In

Table 2 | Results from four GLM analyses on difficulty ratings, η^2 (eta-squared).

Analysis/Condition	Step (df = 1)			Context (df = 1)			Repetition (df = 1)		
	F(1, 11)	p	η^2	F(1, 11)	p	η^2	F(1, 11)	p	η^2
Intensity	74.4	<0.01	0.32	15.4	<0.01	0.05	0.05	0.83	<0.01
Spectral envelope	134.4	<0.01	0.47	6.8	0.02	0.03	0.42	0.53	<0.01
Temporal envelope	61.2	<0.01	0.41	15.1	<0.01	0.05	0.06	0.81	<0.01
F0	196.9	<0.01	0.58	11.46	<0.01	0.03	0.34	0.57	<0.01

the DEC blocks (see Figure 3 top panel), the experiment started with the maximum distracter attenuation (38 phon—black line, starting on the far right of the x-axis). At this point the distracter notes were of low intensity (27 phon) and the difficulty ratings for segregating the melody were very low. As the experiment progressed (moving leftwards on the x-axis), the distracter notes became louder, and the difficulty ratings began to increase up to a final average difficulty of ~0.61 when the melody and distracter notes were presented at equal intensities. In the INC blocks however (red line, with the experiment moving from left to right on the figure), the pattern of difficulty ratings was not simply the reverse. At the beginning of the INC blocks, even though the stimuli were the same as at the end of the DEC blocks, the average difficulty rating was almost the maximum (compared to 0.61 for the end of the DEC blocks).

In order to understand the relationship in CI users between the physical property of intensity in phons, and perceptual loudness in sones, it is useful to understand how sound pressure level is mapped to stimulation current level and a predicted loudness in a CI. All the CI brands work slightly differently, but as all participants in this study were fitted with the same brand (Cochlear Ltd.), only this implant will be addressed. To set the relationship between sound pressure level and current level, the clinician first increases the current level of a single channel until the patient starts to perceive a sensation. This threshold level (T-level) is usually associated with sounds at 25 dB SPL. Then the audiologist increases the current level until the patient reports a comfortably-loud level (C-level) which is associated with a sound at 65 dB SPL. Therefore, any sounds below 25 dB SPL will not be transmitted, and sounds above 65 dB SPL will be limited to the C-level. At distracter attenuation levels of ~20–25 phon attenuation, the difficulty ratings reached a minimum. In the pitch range of the experiment, this level of attenuation resulted in distracter notes that were below 25 dB SPL, too low for the CI users to perceive.

These results highlight the importance of the previous context in the melody segregation task—when the listeners had a chance to hear the melody with distracter notes at a very low intensity at the beginning of the experiment, they were able to hear the melody more easily as the experiment progressed and the distracter notes became louder, even in the most challenging conditions. If they were presented with the most challenging conditions first, however, the task was more difficult overall (not only at the start). In addition to the overall higher difficulty ratings in INC compared to DEC blocks, the average difficulty ratings in INC blocks did not follow a strictly monotonic pattern—they gradually decreased as the distracter attenuation increased, but

then surprisingly started to increase again once the attenuation increased over 25 phons. Neither of these results were found in our earlier study in normally-hearing listeners (Marozeau et al., 2013).

In the INC blocks, the increase in difficulty ratings at distracter attenuation levels above 25 phons is still surprising. However, an inspection of the individual responses revealed that only 4 of the 12 participants showed this non-monotonic pattern (2 showed in only one repetition, 1 had consistently high difficulty ratings at all attenuation levels, and only one showed this behavior on both repetitions). It is possible that some participants might have been confused by the fact that they did not hear any distractors toward the end of the INC blocks. The analysis was repeated but only including attenuation steps larger than 29 phons and no effect of step was found. Therefore, the change in difficulty at these levels is not related to the change in attenuation of the distractor.

Another surprising result was the fact that the distracter attenuation level at the 0.5 difficulty rating point was less than that found in our previous study with normally-hearing listeners (Marozeau et al., 2013). For the CI users in this study, the distracter needed to be attenuated by 8.7 phons to reach the 0.5 difficulty rating point in the INC blocks and only by 1.7 in the DEC blocks, compared to an average of 10.2 phons for the normally-hearing listeners (Marozeau et al., 2013). The normally-hearing listeners required more attenuation of the distracter notes in order to reach the 0.5 difficulty rating point than the CI users. This apparently paradoxical result can be explained in terms of the loudness growth function applied by the CI sound processor. Based on McKay et al. (2003) the loudness growth function is steeper in CI users than in normally-hearing listeners at very high levels (approximately halving the loudness every 5 dB) and gradually becomes shallower and close to the slope for normal hearing at mid-levels (halving the loudness every 10 dB). Therefore, the lower difficulty ratings for CI users might not suggest that they require less loudness difference to segregate the melody, but rather reflects the fact that due to the steeper loudness growth function with electric stimuli they experience more change in loudness for a given physical change than in normal hearing.

The effect of the temporal envelope

Studies on the music abilities of CI listeners often report poor perception of pitch but preserved perception of rhythm (for a complete review see McDermott, 2004). This can be explained partly by the sound-processing employed in CIs. The input sound is filtered into 22 channels with center frequencies between 125

685 and 8000 Hz. In each channel the amplitude of the temporal envelope is used to derive the current level of biphasic pulses delivered
686 at a rate varying from 250 to 3500 pulses per second (pps, typically
687 set to 900 pps). At 900 pps, a pulse will be sent every 1.1 ms.
688

689 This period is less than the measure of temporal resolution in
690 normal hearing listeners measured by the smallest detectable gap
691 length ranging from 2 to 20 ms (for a review see Verhey, 2010).
692 The durations of the stimuli used in the current study varied
693 from 60 to 160 ms FDHM. Therefore, the sound processor itself
694 does not impose any limitations on the perception of the different
695 temporal envelopes used in the current study.

696 Overall the results in the INC block of the CI participants
697 are very close to our previous results in normally-hearing non-
698 musicians, who needed a distractor to melody impulsiveness ratio
699 of 52% to reach the .5 difficulty rating level. In the DEC blocks
700 the results are closer to the musicians who needed a distractor to
701 melody impulsiveness ratio of 62%.

702 *The effect of the spectral envelope*

703 Compared to normal hearing listeners, CI listeners needed a
704 larger difference in spectral envelope to perceive the target
705 melody. This result shows the difficulty that CI listeners have in
706 perceiving timbre difference based only on spectral cues.
707

708 The target stimuli were composed of 10 harmonics with 3 dB
709 attenuation per harmonic. The F0 was presented at between 47
710 and 53 dB SPL. Therefore, the tenth harmonic was presented at
711 levels from 20 to 26 dB SPL and was unlikely to be processed, as
712 most T-levels were set at 25 dB SPL. The number of harmonics
713 processed was highly dependent on the additional attenuation.
714 With 1 dB additional attenuation, only 6 out 10 harmonics will be
715 presented at levels above 25 dB SPL. With 3 dB additional atten-
716 uation only 4 harmonics will be processed. And after 8 dB only
717 two harmonics will be processed. It should then be theoretically
718 possible to discriminate the target and the distractor by focusing
719 on that last harmonic.

720 *The effect of fundamental frequency*

721 The results of the fundamental frequency condition show that
722 the 0.5 difficulty rating points were reached when the distractor
723 ranged between midnote 56 and 64 in the INC blocks and
724 between 58 and 67 in the DEC blocks. As the target melody ranged
725 between 67 and 74, three semi-tones separation was needed in
726 the INC blocks to allow the melody to be segregated from the
727 distractor notes. This difference corresponds to the minimum
728 F0 separation needed for CI listeners to be able to discriminate
729 two notes (Gfeller et al., 2002). In the DEC blocks, the 0.5 diffi-
730 culty rating was reached with one note overlap between the target
731 and the distractor. This result is similar to normally-hearing non-
732 musician listeners (Marozeau et al., 2010), suggesting that despite
733 degraded hearing, CI users report similar difficulty ratings in this
734 task when the context is clearly outlined.
735

736 *The effect of context*

737 The context factor affected difficulty ratings across all the acoustic
738 cues. The change in difficulty ratings as each acoustic parameter
739 changed depended on the direction of the change in the acoustic
740 cues. This was significant for intensity, temporal envelope and F0,
741 but not for the spectral envelope.

742 That the context had a large and significant effect was unex-
743 pected. It might be speculated that as in their everyday life experi-
744 ence, hearing impaired listeners compensate for their hearing loss
745 by using any possible cues, such as visual information, syntac-
746 tic context, or the distracter note context information available in
747 this experiment.

748 The effect of age should also be considered. The CI and NH
749 listeners differ in their average age (CI mean age 71.7 years, SD 8.7
750 years, NH mean age 28.0 years, SD 4.8 years). It might be possible
751 that both groups differ in their auditory working memory ability.
752 As the target melody was required to be learnt, the younger NH
753 group could remember it more easily and did not need extended
754 repetitions with no distractors as with older CI groups in the DEC
755 condition.
756

757 **EXPERIMENT 2**

758 Experiment 1 reported the amount of physical change in four
759 acoustic cues that was required for CI users to be able to segre-
760 gate a repeating melody with a difficulty rating of 0.5. Experiment
761 2 aimed to recast these physical differences in terms of percep-
762 tual salience using a dissimilarity rating paradigm and multi-
763 dimensional scaling analysis (MDS). We have previously used
764 these techniques in normally-hearing listeners (Marozeau et al.,
765 2013).
766

767 **PARTICIPANTS**

768 A total of 8 CI recipients participated in Experiment 2 (including
769 3 who participated in Experiment 1). **Table 1** lists demographic
770 and hearing-related information for all participants. The recruit-
771 ment was conducted through the Cochlear Implant Clinic at the
772 Royal Victorian Eye and Ear Hospital. All the participants gave
773 written informed consent and were compensated for their travel
774 expenses.
775

776 **STIMULI AND PROCEDURE**

777 In Experiment 2, the target melody from Experiment 1 was pre-
778 sented twice in succession, with no distracter notes. The first
779 melody in the pair differed from the second by 1, 2, 3, or 4 of
780 the same acoustic parameters as in Experiment 1 simultaneously
781 (fundamental frequency, intensity, and the spectral and temporal
782 envelopes). Sixteen of these combinations were randomly cho-
783 sen and constructed. The stimuli were presented at an intensity
784 step of either 65, 63, 61, 59, 57, or 55 phons, with an addi-
785 tional attenuation per harmonic of either 3.55, 2.86, 2.24, 1.69,
786 1.19, 0.75, 0.35, or 0 dB, a FHDM of either 119, 126, 133, 142,
787 150, or 160 ms and a base F0 (of the first note) ranging from
788 C3 to G3.

789 Experiment 2 consisted of a training phase and an experimen-
790 tal phase. In the training phase, listeners were presented with each
791 of the 16 stimuli in random order to acquaint them with the range
792 of possible differences in the set of stimuli. The listeners con-
793 trolled the delivery of the stimuli by pressing one of 16 buttons
794 (one for each stimulus), and were instructed to continue listening
795 as long as they wanted to after each stimulus was heard at least
796 once.
797

798 In the experimental phase, the participants were presented
799 with the same stimuli composed of every possible pair of
800

799 the 16 stimuli in random order, totaling 120 pairs. A single
 800 pair was presented in each trial. In each trial, the partici-
 801 pants were instructed to judge how similar the pairs were, and
 802 to respond by moving a cursor on a slider bar labeled from
 803 “most similar” to “least similar.” Listeners could listen to the
 804 pair as many times as they wanted, by pressing a “listen again”
 805 button. When they were satisfied with their judgment, they
 806 pressed a “validate” button, and the next trial began. The order
 807 within pairs and the order of pairs was random, and a differ-
 808 ent randomization was used for each session and subject. For
 809 each pair presented, the dissimilarity response was stored in
 810 a matrix as a continuous value ranging from 0 (similar) to 1
 811 (different).

812 As the factor step is a different physical quality between
 813 conditions, it is not possible to compare the slope of each
 814 condition. One needs to be able to convert the physical scale
 815 to perceptual distance, which can using the MDS method
 816 detailed below.

817 The experimental interface and the data collecting software
 818 were implemented in MAX/MSP 6. Stimuli were played back
 819 through a soundcard (MOTU I/O-24) and loudspeaker (Genelec
 820 8020APM) positioned on a stand at the listener’s ear height, 1 m
 821 from the participant’s head.

822 **ANALYSIS**

823 The dissimilarity matrix of each participant was first analyzed
 824 through a cluster analysis to identify any possible outliers.
 825 No outliers were identified so all the matrices were aver-
 826 aged together. Because the stimuli were designed based on
 827 four clear physical dimensions known to induce four corre-
 828 sponding perceptual dimensions, the MDS algorithm was con-
 829 strained to match an expected physical space created based
 830 on the characteristic of the stimuli using the SMACOF pack-
 831 age in R.2.15.3. This constraining differs from classical MDS
 832 methods where the distance between each pair of stimuli is
 833 derived by all the dissimilarities measured within the set of the
 834 stimuli.

835 By constraining the MDS, the correlation between the per-
 836 ceptual and physical dimension was maximized (i.e., the slope
 837 between the physical parameter and its perceptual association).
 838 Although the order of each stimulus was constrained on each
 839 dimension, the relative contribution of each dimension (the slope
 840 of each dimension) was not.

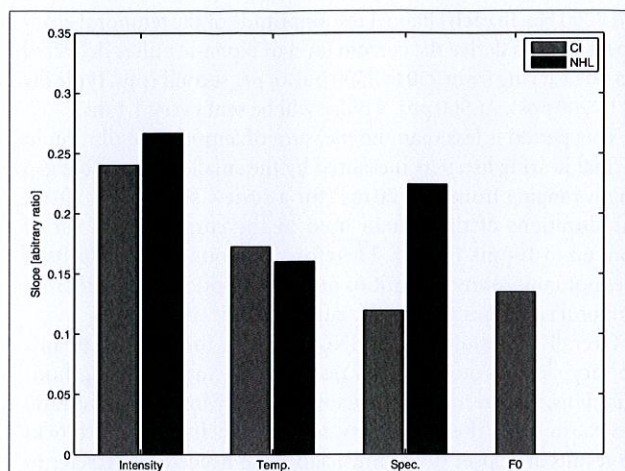
841 As in a classical MDS, the physical solution was derived by
 842 minimizing the stress function S :

843
$$S = \sum_{i < j \leq n} (d_{ij} - \partial_{ij})^2 \tag{1}$$

844 where ∂_{ij} is the averaged dissimilarity judged between the stimuli
 845 i and j and d_{ij} is the physical distance extracted from the 16 * 4
 846 output matrix Y :

847
$$d_{ij} = \sqrt{\sum_{n=1}^4 (y_{in} - y_{jn})^2} \tag{2}$$

848 where y_{in} is the element $[i,n]$ of Y .



856 **FIGURE 4 |** The slope of the regression line between the physical
 857 parameter step and the MDS coordinate for the cochlear implant users
 858 in each condition in the current study (red bars), compared with the
 859 same results from our previous study in normal hearing listeners
 860 (Marozeau et al., 2013, black bars). The F0 was not tested in the normal
 861 hearing listeners (NHL).
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873 The output configuration Y is constrained to be the results
 874 from the multiplication of a 16×4 matrix X by a diagonal 4×4
 875 matrix, C .

876
$$Y = XC \tag{3}$$

877 Where each of the 4 columns of X corresponds to a physical
 878 dimension and each row represents the physical characteristic of
 879 the stimulus on those dimensions.

880 **RESULTS**

881 **Figure 4** shows the slope of the regression line between the
 882 physical parameter step and the MDS dimension for the CI
 883 users in each condition in the current study, compared with the
 884 same results from our previous study in normal hearing listen-
 885 ers (Marozeau et al., 2013, note that the slope for NH listeners
 886 has been re-calculated for this graph using the constrained MDS
 887 technique used in the current study).

888 The slope indicates how much physical change is needed in
 889 order to reach a defined perceptual distance. Note that a differ-
 890 ence of a given number of physical steps does not necessarily
 891 correspond to the same magnitude of perceptual difference for
 892 different acoustic cues, so it is not meaningful to compare the
 893 slope between conditions, but it is possible to compare the slope
 894 between groups. Of particular note, the slope in the Spectral
 895 Envelope condition for the NH listeners is about twice the slope
 896 for the CI users, meaning that twice the number of physical steps
 897 in the Spectral Envelope condition were required to reach the
 898 same perceptual magnitude change for CI users compared to NH
 899 listeners.

900 Based on the slopes of the functions relating physical param-
 901 eter changes with perceptual difference ratings found through the
 902 MDS analysis in Experiment 2, the results of Experiment 1 were
 903 re-scaled into perceptual distance units on the x-axis (**Figure 5**).
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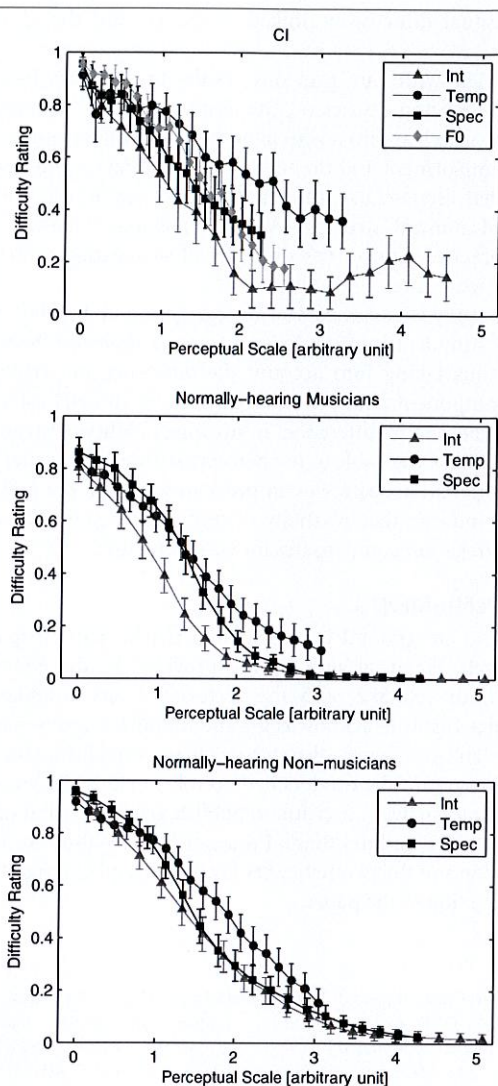


FIGURE 5 | Replots the difficulty ratings from Experiment 1, but with a different abscissa based on a perceptual scale determined from dissimilarity ratings (Experiment 2). The error bars show the standard error of the mean.

The top panel of Figure 5 shows the results from CI users in the four conditions of Experiment 1 on the same perceptual scale. As the context had a significant effect, only data from the INC blocks is shown. In these blocks the experiment starts with the target melody and distracter notes sharing the same physical parameters, so all conditions start with the target melody very difficult to perceive.

Figure 5 shows that for CI users (top panel), intensity is the most efficient stream segregation cue i.e., the smallest perceptual difference in intensity reduces the difficulty of segregating the melody from the distracter notes. The opposite is true for the temporal envelope—a perceptually-large change in impulsiveness is needed to allow the melody to be segregated from the distracter notes.

The analysis from Experiment 1 was repeated, except that the dependent variable is now the perceptual distance and not the acoustic cue step level. In order to avoid missing data in some conditions only perceptual distances up to a value of 2.3 were considered. The analysis revealed that (1) difficulty ratings in the Intensity condition were lower than the three other conditions ($p < 0.001$), (2) difficulty ratings in the Temporal Envelope condition were larger than the three other conditions ($p < 0.001$), and (3) difficulty ratings in the F0 condition were not significantly different from the Spectral Envelope condition ($p = 0.14$).

DISCUSSION

Figure 4 shows that in the Intensity condition, the same amount of physical change induces a larger amount of perceptual change in CI users compared to NH listeners. This increase is in agreement with the literature suggesting that at comfortable levels CI users experience a steeper loudness growth function (McKay et al., 2003). In the Temporal Envelope condition the slope for CI users and NH listeners is similar. This confirms previous suggestions that temporal envelope cues are transmitted well by CIs, and also suggests that a given change in temporal envelope cue is perceived similarly for CI users and NH listeners. Finally the slope of the spectral envelope for CI users is about half the slope of the NH listeners. In order to induce the same change on the perceptual dimension of brightness (correlated with spectral centroid), the physical difference needs to be double in CI listeners compared to NH listeners.

OVERALL DISCUSSION

Figure 5 shows the data from NH musicians and non-musicians from our previous study, re-analyzed to follow the analysis in the current study (lower panels). As with the CI listeners in the current study, the temporal envelope cues required more perceptual difference between melody and distracter for the listeners to be able to segregate the melody from distracter notes. We previously speculated (Marozeau et al., 2013) that temporal envelope cues required the most perceptual difference in order to induce streaming because of the great variability between the durations of phonemes in spoken language. Durations between adjacent phonemes can vary greatly without causing the single speech stream to segregate into two. The temporal variability of English speech was measured by Patel and Daniele (2003) by using a measure of “normalized Pairwise Variability Index” $nPVI$:

$$nPVI = \frac{100}{m-1} \times \sum_{k=1}^{m-1} \left| \frac{2(d_k - d_{k+1})}{(d_k + d_{k+1})} \right| \tag{4}$$

where m is the number of vocalic intervals (sequences of consecutive vowels that might or might not belong to the same syllable or word) or musical notes in an utterance, and d_k is the duration of the k th interval. It is possible to convert the impulsiveness ratio, r into an equivalent $nPVI$ using the following equation:

$$nPVI = 2 \frac{1-r}{1+r} \tag{5}$$

In the DEC blocks, the nPVI required for CI users to judge that the melody was easy to hear (rating at 0.5 difficulty) was 66.66 which is similar to the nPVI found for English language (66.99). In musicians with normal hearing the nPVI was 47.3. This result is very similar to the nPVI of English classical music, 46.91 (Patel and Daniele, 2003). Normally-hearing non-musicians also show a nPVI of 63.7, closer to the nPVI of English speech. As CIs accurately transmit the temporal envelope of sounds, these observations suggest that CI recipients, similarly to non-musician NH listeners, start to segregate two streams when the difference between them is larger than the average temporal variability characteristics of speech.

It has also been shown that the statistical regularities of sound signals can be used by the brain to derive the probability of the next item in a sequence of auditory events (for a review see François and Schön, 2013), and may serve as the basis of language or music learning. In normal hearing, the learning of these regularities can occur through passive exposure, or actively via music training. Similarly, CI users must re-learn the new statistical properties of the auditory sensation delivered via their implant.

CONCLUSIONS

The most efficient streaming cue for CI users was loudness (the perceptual correlate of intensity). This was also the case in our previous study in normal hearing listeners with musical background. On the other hand, similarly for the normal hearing listeners without musical background, a greater difference on the perceptual dimension correlated to the temporal envelope is needed for stream segregation in CI users. No differences in streaming efficiency were found between

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