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Perceptual Differences Between Low-Frequency Analog and Pulsatile Stimulation as Shown by Single- and Multidimensional Scaling

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Abstract

Cochlear-implant users who have experienced both analog and pulsatile sound coding strategies often have strong preferences for the sound quality of one over the other. This suggests that analog and pulsatile stimulation may provide different information or sound quality to an implant listener. It has been well documented that many implant listeners both prefer and perform better with multichannel analog than multichannel pulsatile strategies, although the reasons for these differences remain unknown. Here, we examine the perceptual differences between analog and pulsatile stimulation on a single electrode. A multidimensional scaling task, analyzed across two dimensions, suggested that pulsatile stimulation was perceived to be considerably different from analog stimulation. Two associated tasks using single-dimensional scaling showed that analog stimulation was perceived to be less Clean on average than pulsatile stimulation and that the perceptual differences were not related to pitch. In a follow-up experiment, it was determined that the perceptual differences between analog and pulsatile stimulation were not dependent on the interpulse gap present in pulsatile stimulation. Although the results suggest that there is a large perceptual difference between analog and pulsatile stimulation, further work is needed to determine the nature of these differences.

Keywords

analog, pulsatile, pitch scaling, multidimensional scaling, cochlear implant, amplitude modulation

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Introduction

Current commercial cochlear implants from the five major cochlear-implant companies (Advanced Bionics, Cochlear, Med-El, Nurotron, and Oticon Medical) are all multichannel devices that use pulsatile stimulation. The only device for which analog stimulation is recommended by the manufacturer is a single-channel device from AllHear (House & Vinod, 2003), previously known as the House/3M cochlear implant (House, 1976), which is predominantly targeted as a low-cost device for lower income countries (House & Vinod, 2003). The earliest cochlear-implant research, however, was with analog stimulation (Djourno & Eryies, 1957; House & Urban, 1973; Merzenich, Michelson, Pettit, Schindler, & Reid, 1973; Michelson, 1971; Simmons, 1966), which led to a number of analog cochlear implants that could be used in daily life. Some of these implants only provided stimulation on a single electrode (i.e., single channel) such as the House/3M (House & Urban, 1973), Vienna (Hochmair-Desoyer, Hochmair, Burian, & Fischer, 1981), and External Pattern Input group (Douek & Faulkner, 1987) devices. Other implants provided

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stimulation on multiple electrodes (i.e., multichannel) such as those from UCSF/Storz (Merzenich, 1985), Ineraid (Parkin, McCandless, & Youngblood, 1987), and Project Ear (Evans, 1991). While single-channel analog stimulation can aid lip-reading and improve the recognition of environmental sounds (Bilger & Black, 1977), it provides only limited open-set speech recognition (Hochmair-Desoyer et al., 1981; Tyler, 1988). Substantially better open-set speech recognition is provided by multichannel analog stimulation (Gantz et al., 1988; Tye-Murray, Gantz, Kuk, & Tyler, 1988).

A major disadvantage of continuous analog stimulation from multiple channels is that the currents from multiple electrodes spread in the conductive medium of the cochlea such that the distant cochlear nerve fibers are excited by the combined current from several electrodes (Merzenich, Schindler, & White, 1974; Simmons & Glattke, 1972). It was therefore typically considered necessary to use bipolar stimulation for multichannel analog stimulation because bipolar stimulation might lead to less current spread than monopolar stimulation (Merzenich & White, 1977). Xu, Zwolan, Thompson, and Pfingst (2005) demonstrated in a small study with 10 patients that switching to monopolar analog stimulation did not significantly affect speech recognition, but the use of bipolar mode for analog stimulation nonetheless remained standard practice.

Modern cochlear implants all use pulsatile stimulation for their clinical sound coding strategies because the pulses can be temporally interleaved to reduce the summation of electric fields across channels, which occurs with simultaneous stimulation, including multichannel analog stimulation. This concept was first proposed by Merzenich and White (1977) and later made more widely known as the continuous interleaved sampling (CIS) strategy by Wilson et al. (1988, 1991). The reduced channel interaction with interleaved pulses made it possible to use monopolar stimulation. Because operating currents are lower for monopolar stimulation than for bipolar, as evidenced by lower thresholds (Eddington, Dobelle, Brackmann, Mladejovsky, & Parkin, 1978; Shannon, 1983; Simmons, 1966) and lower current required to reach most comfortable level (Battmer et al., 2000), battery life was extended enabling lower capacity batteries. In particular, the use of monopolar stimulation engendered by interleaved pulses enabled the transition from body-worn to behind-the-ear speech processors (Lehnhardt, Gnadeberg, Battmer, & von Wallenberg, 1992). There were therefore commercial incentives to move away from analog stimulation. Although the cochlear implants manufactured by Advanced Bionics today can still deliver multichannel analog stimulation, none of the major companies currently recommend the clinical fitting and use of analog strategies.

The performance benefits, however, of pulsatile stimulation have not been unequivocal. An initial study by Wilson, Finley, and Lawson (1990) compared continuous analog stimulation with an interleaved pulsatile strategy in six patients implanted with the UCSF device, where each patient had use of two of four electrodes. They found that for overall speech comprehension, some patients performed better with analog stimulation and some with pulsatile; analog stimulation appeared to provide better speech comprehension for vowels and interleaved pulses for consonants. Similarly, a comparison of analog stimulation and CIS in five patients by Schindler, Kessler, and Haggerty (1993) found that one performed better with analog stimulation and another preferred analog stimulation but performed better with CIS; the authors attributed preference of analog stimulation to better nerve survival. Other small studies appeared to show more benefit for CIS. For example, a study by Dorman and Loizou (1997) with just one Ineraid patient found that CIS improved performance compared with analog stimulation. A well-known study by Wilson et al. (1991) with seven participants also found that participants performed better with CIS than analog stimulation on speech recognition tasks, but the comparison was between 5- and 6-channel CIS and 4-channel analog. Similarly, a study by Frijns, Briaire, de Laat, and Grote (2002) with 10 patients found that all got higher scores on a CVC test using CIS, or a variant of it.

Later larger studies with the Advanced Bionics Clarion cochlear implant, which is capable of both analog and pulsatile stimulation, produced further mixed results. Battmer, Zilberman, Haake, and Lenarz (1999) examined the performance of 22 German adults who were postlingually implanted; 20 of the 22 participants were evaluated with the analog strategy. Of the two that were not evaluated, one was unable to achieve sufficient loudness with analog stimulation and the other dropped out of the experiment before evaluation. The remaining 20 participants all received training with both strategies and were asked to keep a diary about their experiences with each strategy. They were evaluated at 2 weeks, 6 weeks, and 3 months with various speech tests and questionnaires. After 3 months, 50% of participants preferred the analog strategy and 50% preferred CIS. The speech test results showed that participants who preferred analog stimulation demonstrated good results with both strategies, while the group that preferred CIS only did well using the CIS strategy. Those subjects who preferred simultaneous analog stimulation (SAS) had higher electrode impedances, lower thresholds, and lower "most comfortable" loudness levels, which were presumed to have arisen from more modiolar-hugging electrodes.

Battmer et al. (2000) conducted a similar study in a pediatric population with 22 children aged between 4 and 13 years old. All the children originally used the CIS strategy. Sixteen of them could be fitted with the analog strategy, of whom 11 preferred it. Of the six children who could not be fitted with SAS, five required M-levels that were too high and one could not report reliable loudness levels. Some reported more background noise with the analog strategy than with CIS, but it was considered that this resulted from more hearing in general and that the children would adapt to this increase in noise over time, which they did. As in the original adult study, the group that preferred analog stimulation (69% of the children able to compare) tended to have lower thresholds and most comfortable loudness levels than those who preferred CIS. Two larger studies by Osberger and Fisher using the Clarion implant, one with 71 participants (Osberger & Fisher, 1999) and the other with 58 participants (Osberger & Fisher 2000), both found that a substantial proportion of patients (32% and 28%, respectively) preferred analog stimulation after 3 months. Those who preferred the analog strategy had higher speech recognition scores than those who preferred CIS, which was taken as evidence of a faster rate of learning. These participants also had a shorter duration of deafness than those who preferred CIS. The authors considered that the shorter duration of deafness may be evidence of better neural survival that enabled greater channel independence when using an analog strategy (Osberger & Fisher, 1999).

Other large studies also found that a notable proportion of participants preferred analog stimulation to CIS. A multicenter study by Stollwerck et al. (2001) with 55 participants found that 25% preferred analog stimulation after being evaluated at 3 months. Similarly, another multicenter study with 51 participants found that 41% preferred analog stimulation (Koch, Osberger, Segel, & Kessler, 2004). In both studies, there may have been an effect of unequal exposure to the strategies, but a well-controlled crossover trial by Zwolan et al. (2005) with 25 participants still found that a notable proportion (16%) preferred analog stimulation at the end of the 6-month evaluation—with those preferring analog showing a very strong preference to it. Participants tended to perform best with the strategy they preferred.

Following the transition by Advanced Bionics from CIS and SAS strategies to the HiRes pulsatile strategy, there have been no direct comparisons between the preference of analog and pulsatile strategies. Whilst Koch et al. (2004) did ask participants to rate their preference for the 8-channel and 16-channel strategies, this was done after the second phase of the study, which was 3 months after they had been swapped from an 8-channel to a 16-channel strategy. Nonetheless, 1 year after the start of the study, two participants (4%) still preferred to use an 8-channel strategy, although it is not clear whether this was CIS or analog. Even now, however, there is anecdotal evidence that some patients still strongly prefer analog stimulation—to the extent that they continue use analog stimulation with old body-worn devices rather than upgrade to a behind-the-ear processor to pulsatile stimulation without cost (T. Nunn, personal communication).

This preference of some users for analog stimulation, although now largely historical, warrants further investigation, particularly in the light of various recent attempts to deliver the fine-time structure with pulsatile stimulation (e.g., Arnoldner et al., 2007; Vermeire, Punte, & Van de Heyning, 2010). This cue, which is thought to aid pitch perception (Evans, 1978) and sound localization (McAlpine, Jiang, & Palmer 2001), is largely removed by the CIS strategy but may be provided by analog stimulation. There is some evidence that better performing users of the Vienna single-channel cochlear implant were able to discriminate vowels based on information provided by fine time structure (Hochmair-Desoyer et al., 1981). Moreover, low-pass filtering of the single-channel speech signal reduced speech comprehension, even when the cutoff was as high as 900 Hz (Hochmair & Hochmair-Desoyer, 1985). Even though there are advantages of pulsatile stimulation, we consider that it may nonetheless be instructive to determine why some cochlear-implant users prefer analog stimulation and whether any underlying causes of this preference can be incorporated into pulsatile strategies.

There have been few studies that have directly examined the perceptual difference between basic analog and pulsatile stimulation. Eddington (1980) and Eddington et al. (1978) found that sinusoidal stimulation (analog) led to a larger dynamic range compared with pulsatile stimulation (12–15 dB for analog and 5–7 dB for pulsatile). Shannon (1981) correspondingly found that sinusoidal stimulation led to shallower loudness-growth functions. In terms of sound quality, Michelson (1971) reported that participants could perceive a "tonal" difference between sinusoidal and pulsatile stimulation, although the reported descriptions were timbre related: One of the four patients described sinusoidal stimulation as "bell-like" and pulsatile as "harsh" while another described pulsatile stimulation as "distorted." In contrast, however, Eddington et al. (1978) found that four participants could not distinguish between sinusoidal and pulsatile stimuli when they were matched for loudness and pitch and concluded that "one waveform is no better than any other." For speech stimuli, Battmer et al. (1999) found that adults who preferred analog stimulation to CIS considered that analog stimulation led to a "deeper" sound quality compared with CIS. In their following study with children (Battmer et al., 2000), analog stimulation was reported as being more pleasant, softer, and more information bearing than pulsatile stimulation.

To compare analog to pulsatile stimulation, it is first important to define how pulsatile stimulation can be used to provide a given frequency. Pulsatile stimulation can represent temporal information either by low-rate stimulation with a fixed amplitude (i.e., an unmodulated pulse train; UMP) or by amplitude modulation of a high-rate pulsatile carrier (i.e., an amplitude-modulated pulse train; AMP). Both AMP (e.g., CIS; Wilson et al., 1991) and UMP stimulation (i.e., FSP, FS4; Riss et al., 2014) have been used to encode temporal information in clinical strategies. Similarly, both AMP (e.g., Galvin & Fu, 2005; McKay, McDermott, & Clark, 1994; Todd, Mertens, Van de Heyning, & Landsberger, 2017) and UMP (e.g., Landsberger & McKay, 2005; Landsberger, Vermeire, Claes, Van Rompaey, & Van de Heyning, 2016; Tong, Blamey, Dowell, & Clark, 1983; Townshend, Cotter, Van Compernolle, & White, 1987) have been used psychophysically to measure temporal performance. However, it is unclear what the perceptual relationship is between these two types of stimulation. It has been demonstrated that when modulation depth is shallow, the pitch of AMP stimulation with a fixed modulation rate is higher than UMP stimulation at the corresponding stimulation rate. However, as modulation depth increases, the pitch of AMP stimulation lowers and becomes similar to that of UMP stimulation at the corresponding stimulation rate (McKay et al., 1994; Vandali, Sly, Cowan, & van Hoesel, 2013). It is intuitive that the pitch lowers with increased modulation depth because with a shallow modulation depth, the percept is likely to be dominated by the rate of stimulation, whereas with an increased modulation depth, it is likely that the modulations become more salient. Although it has been shown that the pitch of AMP stimulation with deep modulations is similar to that of UMP stimulation at the corresponding stimulation rate, it remains unknown how perceptually similar these two stimuli are along other perceptual dimensions.

In this experiment, we aimed to gain further information on perceptual quality and space of analog and pulsatile stimulation using a multidimensional scaling (MDS) task. An advantage of using MDS is that it enables exploration of the parameter space without predefining perceptual dimensions, or qualities associated with the stimuli. In the first experiment (Experiment 1A), an MDS task was used to determine the perceptual dimensions related to changes in stimulation type (i.e., analog, UMP, and AMP at a fixed carrier rate) and stimulation frequency. However, while MDS provides information on the dimensions used to describe a stimulus set, it cannot on its own ascertain the perceptual qualities associated with the dimensions. Therefore, we also asked participants to scale each of the stimuli in terms of how "High" or how "Clean" the sounds were (Experiment 1B). It was found that for a given frequency, AMP and UMP stimuli sounded relatively similar, while analog stimuli sounded different from either AMP or UMP. We hypothesized that the perceptual differences between pulsatile stimulation and analog stimulation may be related to the long interpulse intervals (i.e., where no stimulation is present) found in pulsatile stimulation that are not present in a continuous waveform such as analog. Therefore, in Experiment 2, we investigated whether increasing the carrier rate of AMP (i.e., reducing the interpulse intervals) made the AMP stimuli sound more like analog stimuli. In Experiment 2A, the perceptual space defined by varying carrier rates of AMP stimuli and analog stimulation was measured using a second MDS task. In Experiment 2B, we asked participants to scale how changing of carrier rate affects High and Clean ratings to help interpret the perceptual space defined in Experiment 2A.

General Methods

Participants

A total of 13 postlingually deafened adults implanted with the Advanced Bionics device participated in this study. This device was used because it enabled analog stimulation when used with the Bionic Ear Data Collection System (Litovsky, Goupell, Kan, & Landsberger, 2017). The participants had a mean age of 62.4 years, and all used a pulsatile strategy outside of the study (mean time since implantation 7.7 years). All 13 participants completed Experiment 1A. Twelve of the participants (all except C108 who was excluded for scheduling reasons) completed the remaining experiments. Six participants were tested at the New York University School of Medicine in New York and seven at the University of Southern California in Los Angeles. Participant codes with three digits (e.g., C105) represent participants that were tested at New York University, while participant codes with one or two digits (e.g., C14) represent participants that were tested at the University of Southern California. Participants were recruited and gave informed consent according to the institutional review board regulations at the respective institutions. All participants were compensated for their participation. Specific participant demographic information is presented in Table 1.

Stimuli

All stimuli were presented directly to the participant via Bionic Ear Data Collection System using custom written

Table 1. Participant Demographics.

Code	Age at Testing	Gender	Onset of HL	Etiology	Ear	Implantation Year	Implant / Electrode Array	Strategy
C101	70	M	Progressive	Unknown	RE	2012	HiRes 90K / HiFocus 1J	HiRes-P w/ Fidelity 120
C105	53	F	Progressive	Unknown	LE	Implanted 2005, revised 2010	HiRes 90K / HiFocus 1J	Optima-S
C106	38	M	Progressive	Unknown	RE	2010	HiRes 90K / HiFocus 1J	HiRes-S w/ Fidelity 120
C107	44	F	Progressive	Unknown	RE	2002	CII / HiFocus 1J	Optima-P
C108	64	M	Progressive	Otosclerosis / NIHL	LE	2010	HiRes 90K / HiFocus 1J	Optima-P
C113	79	F	Progressive	Unknown / possible NIHL in WWII	RE	2009	HiRes 90K / HiFocus 1J	HiRes-S w/ Fidelity 120
C7	66	F	Progressive (diagnosed age 1)	High fevers and ototoxicity	LE	2006	HiRes 90K / HiFocus 1J	Optima-S
C9	73	M	Diagnosed at 18 months	Possible Spinal Meningitis	RE	2002	CII / HiFocus	Optima-S
C14	51	M	Diagnosed at 4.5 months	Maternal rubella (first trimester)	RE	2005	HiRes 90K / HiFocus 1J	Optima-P
C19	66	M	Age 49	Sudden Hearing loss (auto-immune)	RE	1999	CII / HiFocus	HiRes-S w/ Fidelity 120
C23	76	F	Severe SNHL diagnosed at age 4	Congenital	RE	2012	HiFocus 90k / Helix	Optima-S
C24	61	F	Progressive	Hereditary	RE	2012	HiFocus 90K / HiFocus 1J	Optima-S
C25	64	M	Progressive	Unknown	RE	2013	HiFocus 90K / Mid-Scala	Optima-S

Note. M = male; F = female; HL = hearing loss; NIHL = noise-induced hearing loss; RE = right ear; LE = left ear; WWII = World War II.

software on a windows computer. Although the specific stimuli varied across experiments, they all consisted of single electrode stimulation using analog sine waves, UMP, or AMP. Figure 1 illustrates how analog, AMP, or UMP stimulation can each be used to convey a given frequency. In this article, the term frequency describes stimulation rate for UMPs, envelope modulation rate for AMPs, and the number of cycles per second of the waveform represented by analog stimulation. Analog sine waves had frequencies of 100, 150, 200, or 400 Hz with a sampling interval of 65 µs. UMP stimuli were presented at 100, 150, 200, and 400 pulses-per-second (pps). AMP stimulation was presented with carrier rates of 750, 1,500, 1,600, 3,000, 6,000, or 12,000 pps (depending on experiment and condition). AMP stimulation was amplitude modulated at 100, 150, 200, or 400 Hz with a modulation depth of 75%. The phase duration for both UMP and AMP stimulation was 226 µs. All pulse trains consisted of cathodic-first biphasic pulses. All stimuli were 750 ms in duration and were loudness balanced to the "most comfortable" loudness level as described in the procedures later. All stimuli were presented by monopolar stimulation on Electrode 2, which for the Advanced Bionics system is an apical electrode. An apical electrode was chosen to minimize the differences between the place pitch at the site of electric stimulation and the rate pitch elicited by our electric stimuli (e.g., Landsberger, Svrakic, Roland, & Svirsky, 2015).

Procedure

Estimation of the dynamic range. A rough estimate of the dynamic range was made for each stimulus for all experiments. Stimuli were initially presented subthreshold, and the amplitude of each stimulus was gradually increased in 5-µA steps until the level of maximal comfort was reached (Level 8 of the Advanced Bionics 10 point loudness scale).

Loudness balancing. All stimuli for all experiments were set to the most comfortable level (Level 6). Loudness balancing of all stimuli used in the tasks was done with a

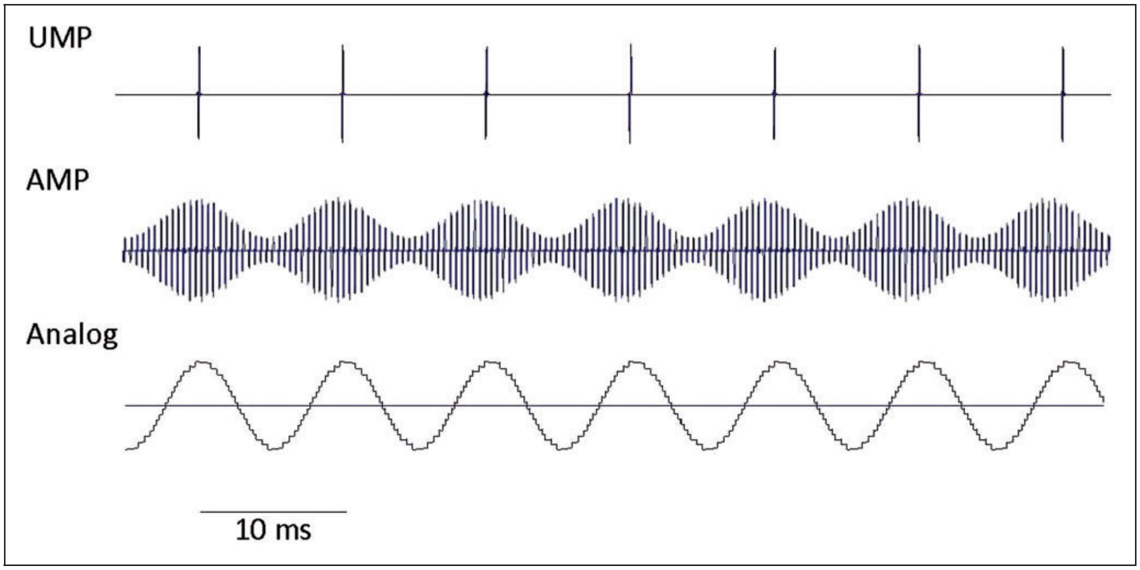

Figure 1. Illustration of how 100 Hz is encoded for the three stimulation types (unmodulated pulse trains: UMP, amplitude-modulated pulse trains: AMP, and Analog). Note that each vertical line for the AMP and UMP stimuli represents a biphasic rectangular pulse, although the phase durations are too short to resolve each phase in the plot. The "Analog" signal is referred to as analog in that it encodes a continuous waveform. However, the waveform is technically digitized using a sampling interval of 65 µs. Nevertheless, this sampled continuous waveform is described as analog in the cochlear-implant literature and is how the simultaneous analog strategy (SAS) from Advanced Bionics delivers analog stimulation.
UMP = unmodulated pulse trains; AMP = amplitude-modulated pulse trains.

loudness-sweeping protocol similar to that implemented in Landsberger, Mertens, Kleine Punte, and Van de Heyning (2014). Stimuli were first presented at the most comfortable level in sets of four sequentially presented stimuli. For each set, participants were asked if any of the stimuli differed in loudness. If so, the amplitudes of the stimuli were adjusted until all sounds were equally loud at the most comfortable level. This was repeated until all stimuli were balanced for loudness. The participants were instructed that the first stimulus remained as constant anchor point for all loudness sweeps. If the participant suggested a change in loudness for the anchor, the other three stimuli were adjusted instead. For example, if the anchor was reported to be quieter than the other three stimuli, the amplitudes of the other three stimuli would be reduced while the amplitude of the anchor would remain fixed. In Experiment 1, the anchor stimulus was 100-Hz analog stimulation. In Experiment 2, the anchor stimulus was 100-Hz AMP with a 750-pps carrier.

Multidimensional scaling (Experiments 1A and 2A). In Experiments 1A and 2A, a typical MDS protocol was used (e.g., Tong et al., 1983) to examine the perceptual relationships between Analog, AMP, and UMP stimulation. The two experiments differed only in the stimulus sets used. All stimuli were played to the participant before each experiment began to familiarize them with the range of possible sounds within the experiment. In each trial, two stimuli were randomly selected from the stimulus set and presented with an interstimulus interval of 300 ms. After each trial, the participant rated how different the two stimuli were from each other by using a mouse to click on a line on the computer monitor that represented a scale from "least different" to "most different." The line location on the monitor was varied on each trial to ensure that the mouse was moved by the participant when making a selection. All pairs of stimuli were presented once in a block of trials. The procedure was repeated until at least five blocks of data were collected. The order of trials was randomized independently for every block tested.

Sound-quality scaling. In Experiments 1B and 2B, the sound quality of various single-channel stimuli was perceptually scaled. In each trial, a single randomly selected stimulus was presented at a most comfortable level for 750 ms. The participant was asked to scale either how High or how Clean the stimulus was by clicking with a mouse on a horizontal black bar with endpoints labeled as "Least High" and "Most High" or "Least Clean" and "Most Clean" depending on the block using a method similar to Landsberger, Padilla, and Srinivasan, (2012). The location along the black bar was converted by our software to a value between 0 and 100 (where 0 represented "Least" and 100 represented "Most"). After each trial, the location of the black bar moved to a new location on the screen to require the participant to move the mouse to a new location after each trial. In a block, all stimuli were scaled once using only one term (i.e., either High or Clean). A minimum of 10 blocks was collected for both Clean and High for all participants. Before the experiment began, participants were played all stimuli to familiarize them with the range of sounds they would be hearing. Experiments 1B and 2B differ only in the set of stimuli used.

Experiment 1A—Multidimensional Scaling of Analog, UMP, and AMP Stimuli With a Fixed Carrier Rate

Methods

An MDS protocol was used as described earlier. The stimulus set included nine stimuli consisting of the three stimulation types (analog, UMP, and AMP) at one of three stimulation frequencies (100, 200, or 400 Hz). The amplitude-modulated stimulus had a fixed carrier rate of 1,600 pps.

Results

The multidimensional scaling data from Experiment 1A were analyzed in a two-dimensional space using the ALSCAL algorithm (Young & Lewyckyj, 1979). The bottom right panel of Figure 2 presents the perceptual space averaged across all participants, while each of the remaining panels represents the perceptual spaces for each participant. MDS data were rotated such that perceptual differences between frequencies were represented by Dimension 1 for all participants. In the average data (bottom right panel), the frequency (indicated by color) of each stimulus was ordered from lowest to highest along Dimension 1 for all three stimulation types (Analog, UMP, and AMP). For a given frequency, all three stimulation types were represented by similar values along perceptual Dimension 1. The r^2 representing the goodness of fit for the two-dimensional ALSCAL analysis was 0.923 suggesting that the two-dimensional space accurately describes the perceptual relationships between the stimuli.

Individual data for most participants had the same characteristics as the average data, in that Dimension 1 represented an ordered change in frequency, while Dimension 2 represented a separation between stimulation types such that the percept induced by analog stimulation was usually further from the percepts induced by AMP and UMP stimulation. For many of the participants (e.g., C107, C108, C7, C9, C19), the differences between the stimulation types were smaller for 400 Hz than for 100-Hz stimulation. This pattern is reflected in the average data. The data from participant C24 were organized by frequency and showed little effect of stimulation type. Participant C9 showed a strong effect of stimulation type at 100 Hz. However, at 200 and 400 Hz, all stimuli regardless of type sound quite similar. As shown in Figure 2, the r^2 for individual participants ranged from 0.645 (C23) to 0.995 (C25) with a median r^2 of 0.863. The individual fits observed for this experiment are similar to other two-dimensional MDS fits with CI participants reported in the literature (e.g., median r^2 for Landsberger et al. [2014] is 0.78, and the median r^2 for Vermeire et al. [2013] is 0.88).

The perceptual distances (in the two-dimensional analysis space) between each pair of stimulation types are plotted for each frequency as well as averaged across frequencies in Figure 3. Error bars represent ± 1 standard error of the mean. A two-way repeated measures analysis of variance (ANOVA) detected main effects of differences between stimulation types, $F(2, 48) = 6.62$, $p < .001$, and frequency, $F(2, 48) = 25.04$, $p < .001$. No interaction between the two factors was observed, $F(4, 48) = 1.92$, $p = .123$. Post hoc t tests collapsing across frequencies detected significant differences between the perceptual distances from Analog to UMP and Analog to AMP (i.e., the difference between dark blue and light blue bars; $t(12) = 2.357$, $p = .036$). Similarly, the perceptual distance between the two pulsatile stimuli was significantly different than the perceptual distances between AMP and analog (i.e., the difference between red bars and dark blue bars; $t(12) = 4.383$, $p < .001$) and UMP and analog (i.e., the difference between red bars and light blue bars; $t(12) = 5.976$, $p < .001$). All three of these comparisons remain statistically significant after Type I error correction using Rom's (1990) method. Post hoc t tests collapsed over stimulation types detected significant differences between the perceptual distances between 100 Hz and 400 Hz, $t(12) = 2.670$, $p = .0204$, and the perceptual distances between 200 Hz and 400 Hz, $t(12) = 3.161$, $p = .008$. These differences remain significant after Type I error correction with Rom's (1990) method. No significant difference between 100 Hz and 200 Hz was detected, $t(12) = 1.787$, $p = .099$. Note that a tutorial explaining how to use Rom's method to control for Type I error is available in the Appendix of Aronoff, Stelmach, Padilla, and Landsberger (2016).

As the primary question of the experiment was to determine the perceptual differences between analog and pulsatile stimulation, an additional two-way repeated measures ANOVA was calculated only for the perceptual differences between analog and the two pulsatile stimulation modes (i.e., the dark and light blue bars of Figure 3). Main effects of the perpetual differences between stimulation types, $F(1, 12) = 5.557$, $p = .036$, and frequency, $F(2, 24) = 4.926$, $p = .016$, as

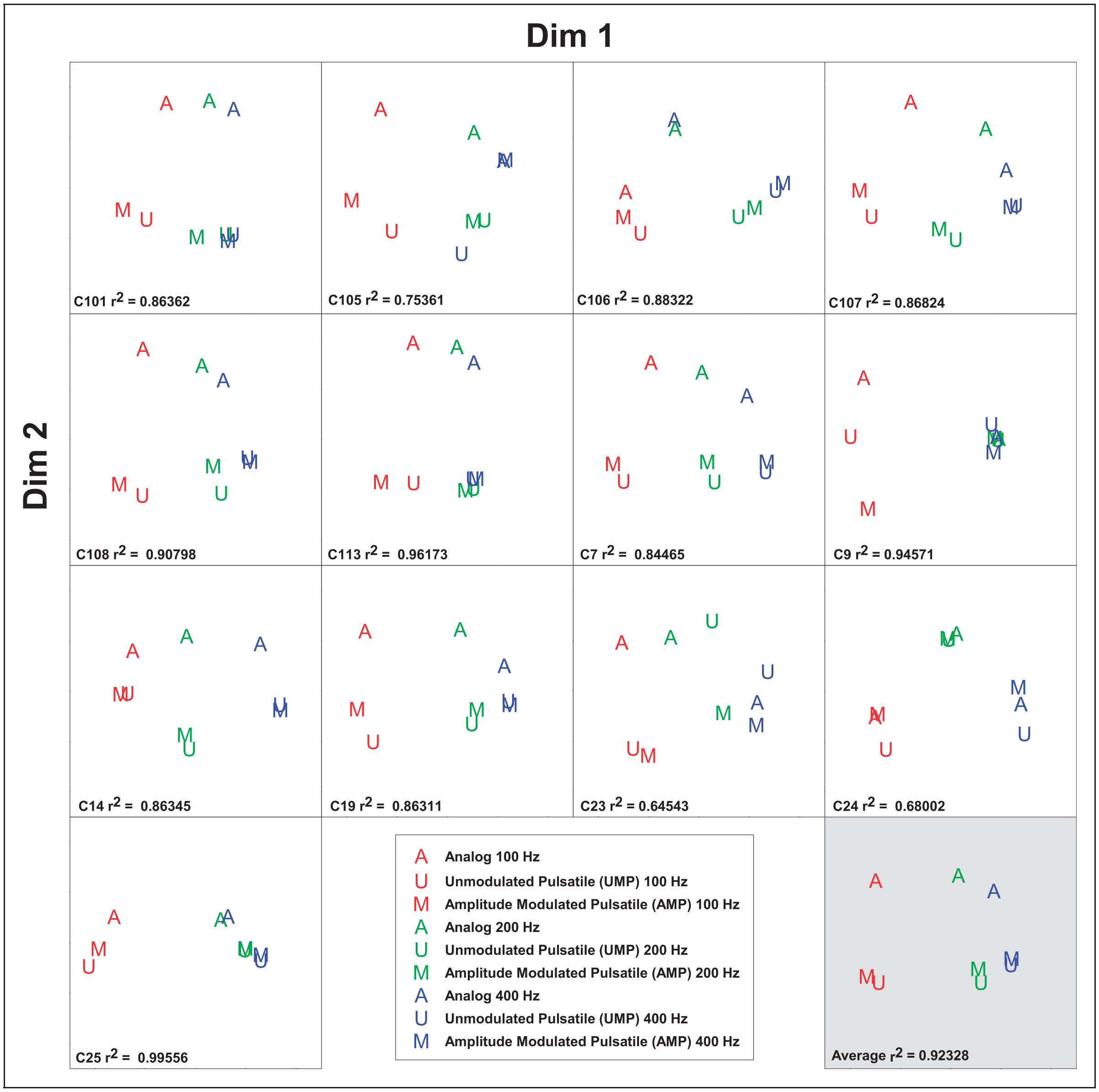

Figure 2. Multidimensional scaling results for all participants tested in Experiment 1A plotted in two dimensions. Different frequencies are denoted by different colors (Red = 100 Hz, Green = 200 Hz, and Blue = 400 Hz), while type of stimulation is denoted by letters (A = analog, U = unmodulated pulsatile, M = amplitude-modulated pulsatile). Each of the 13 panels with white backgrounds shows individual participant results. The corresponding participant code and r^2 value are displayed in the lower left-hand corner of each plot. The plot in the lower right-hand corner with the gray background represents the two-dimensional space represented by the responses averaged across all participants.

well as the interaction, $F(2, 24) = 3.431$, $p = .049$, were detected.

Discussion

While it cannot be determined directly from the MDS data, the correspondence between the order of all the stimuli along Dimension 1 and the fundamental frequency is consistent with the hypothesis that Dimension 1 represents rate pitch. If so, this would indicate that all stimulus types with a common frequency and cochlear location have a similar pitch. However, Analog simulation was perceived differently from either AMP or UMP stimuli along Dimension 2, suggesting that the sound quality difference between Analog and AMP and UMP stimuli was not based on frequency perception. At a given frequency, the distances between AMP and UMP are relatively small suggesting that AMP and UMP stimulation produce similar (but not necessarily indistinguishable) percepts.

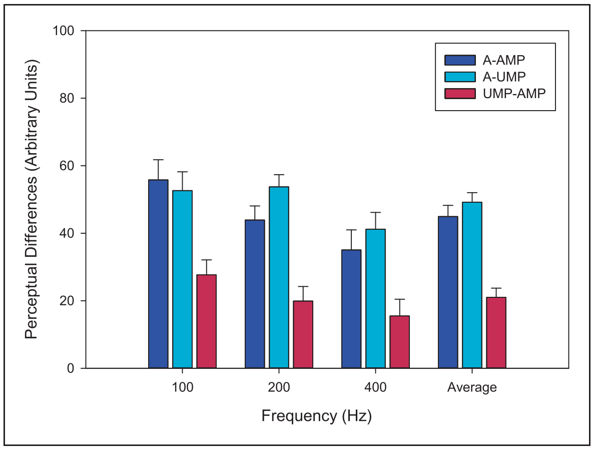

Figure 3. Bar plot showing the perceptual distance between stimulation types for each frequency as well as averaged across all frequencies. Dark blue bars represent the perceptual distance between analog and AMP stimulation types, light blue bars represent the perceptual distance between analog and UMP stimulation bars, and red bars represent the perceptual distance between AMP and UMP stimulation. Error bars represent ± 1 standard error of the mean.
AMP = amplitude-modulated pulse trains; UMP = unmodulated pulse trains.

Experiment 1B—Sound Quality Scaling of Analog, UMP, and AMP Stimuli With a Fixed Carrier Rate

Methods

In Experiment 1B, the sound quality of Analog, UMP, and AMP stimuli was perceptually scaled as described earlier. The stimulus set for Experiment 1B consisted of 12 stimuli (100, 150, 200, and 400 Hz in analog, UMP, and AMP with a 1,600-pps carrier). In a block, all stimuli were scaled once using only one term (i.e., either High or Clean).

Results

The average pitch-scaled values were calculated for each frequency in each stimulation type for all participants. The results for each individual participant are presented in individual panels of Figure 4. The bottom right panel displays the mean results across participants. The responses ranged from values of 0 to 100 with the lower numbers representing lower pitches and higher numbers representing higher pitches. The mean data show that higher frequencies were ranked as higher in pitch. This pattern was consistent across most participants. For a given frequency, the pitch scaling ratings largely overlapped for the different types of stimulation, suggesting that the perception of pitch height was more dependent on the stimulus frequency than the type of stimulation. A two-way repeated measures ANOVA (using stimulation type and frequency as factors and High scaling as a dependent variable) found a main effect of frequency, $F(3, 66) = 9.810$, $p < .001$, but no effect of stimulus type, $F(2, 66) = 0.617$, $p = .55$, or interaction, $F(6, 66) = 1.651$, $p = .1475$. Post hoc tests detected a significant difference between 100-Hz and 400-Hz stimulation, $t(11) = 3.370$, $p = .0063$, between 100-Hz and 200-Hz stimulation, $t(11) = 2.610$, $p = .0242$, between 150-Hz and 200-Hz stimulation, $t(11) = 4.345$, $p = .0012$, between 150-Hz and 400-Hz stimulation, $t(11) = 4.842$, $p = .00052$, and between 200-Hz and 400-Hz stimulation, $t(11) = 3.508$, $p = .005$. No significant differences were detected between 100 Hz and 150 Hz, $t(11) = 1.762$, $p = .106$. After Type I error correction using Rom's (1990) method, all comparisons except between 100 Hz and 200 Hz remained significant.

The average Clean-scaled values were calculated for each frequency in each stimulation type for all participants. The results for each individual participant are presented in individual panels of Figure 5. The bottom right panel displays the mean results across participants. In the mean plot, there appears to be a difference in Clean scaling for each stimulation type and frequency. UMP stimuli tended to be rated as most Clean, while analog stimuli were rated as least Clean. Ratings for AMP stimuli tended to be between UMP and analog ratings. While this pattern was consistent across frequencies, the absolute Clean rating increased with increasing frequencies for all stimulation types. A two-way repeated measures ANOVA detected a main effect of frequency, $F(3, 66) = 8.743$, $p < .001$, and a main effect of stimulation type, $F(2, 66) = 3.813$, $p = .038$. No interaction between frequency and stimulation type was detected, $F(6, 66) = 0.627$, $p = .708$. After Type I error correction using Rom's (1990) method, no significant differences were detected between analog and UMP stimulation types, $t(11) = 2.262$, $p = .045$, analog and AMP stimulation, $t(11) = 1.468$, $p = .170$, or UMP and AMP stimulation, $t(11) = 2.737$, $p = .0193$. Post hoc tests detected a significant difference between 100-Hz and 150-Hz stimulation, $t(11) = 2.915$, $p = .014$, between 100-Hz and 200-Hz stimulation, $t(11) = 3.467$, $p = .0053$, and between 100-Hz and 400-Hz stimulation, $t(11) = 3.352$, $p = .0065$. No significant differences were detected between the other frequencies tested (150 Hz and 200 Hz: $t(11) = 1.479$, $p = .167$; 150 Hz and 400 Hz: $t(11) = 1.446$, $p = .176$; 200 Hz and 400 Hz: $t(11) = 1.231$, $p = .244$). After Type I error correction using Rom's (1990) method, the difference between 100 and 200 Hz and the difference between 100 Hz and 400 Hz remained significant.

As the term Clean was left to the interpretation of the participant, it is possible that the term Clean would be

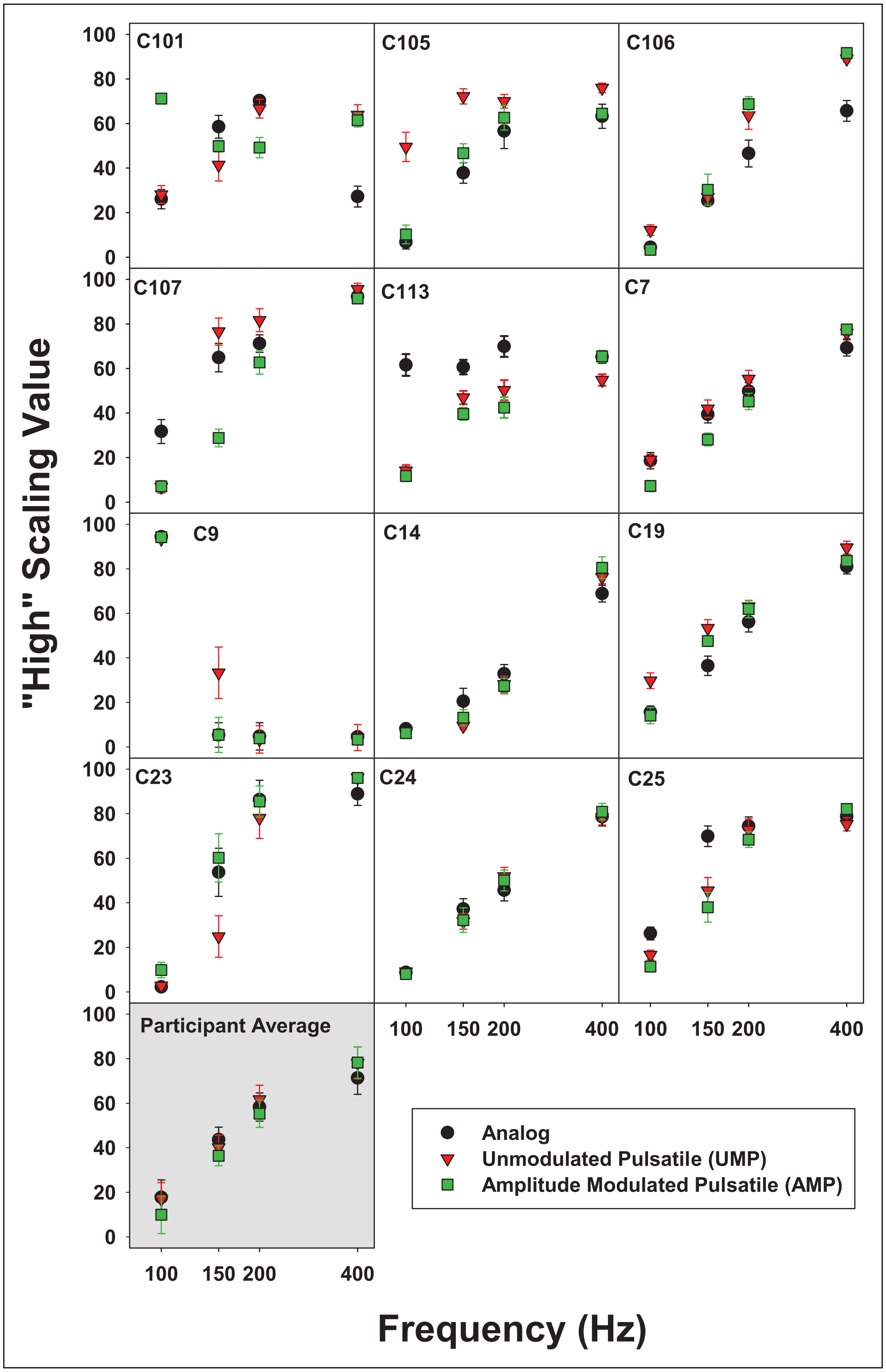

Figure 4. Scatter plot of scaled values in response to the question "How High is the sound?" Points are plotted as a function of frequency. Black circles represent analog stimulation, upside-down red triangles show UMP stimulation, and green squares represent AMP stimulation. The 12 panels with white backgrounds represent results for individual participants. The lower right-hand corner panel with the gray background represents the data averaged across all participants. Error bars represent ± 1 standard error of the mean.

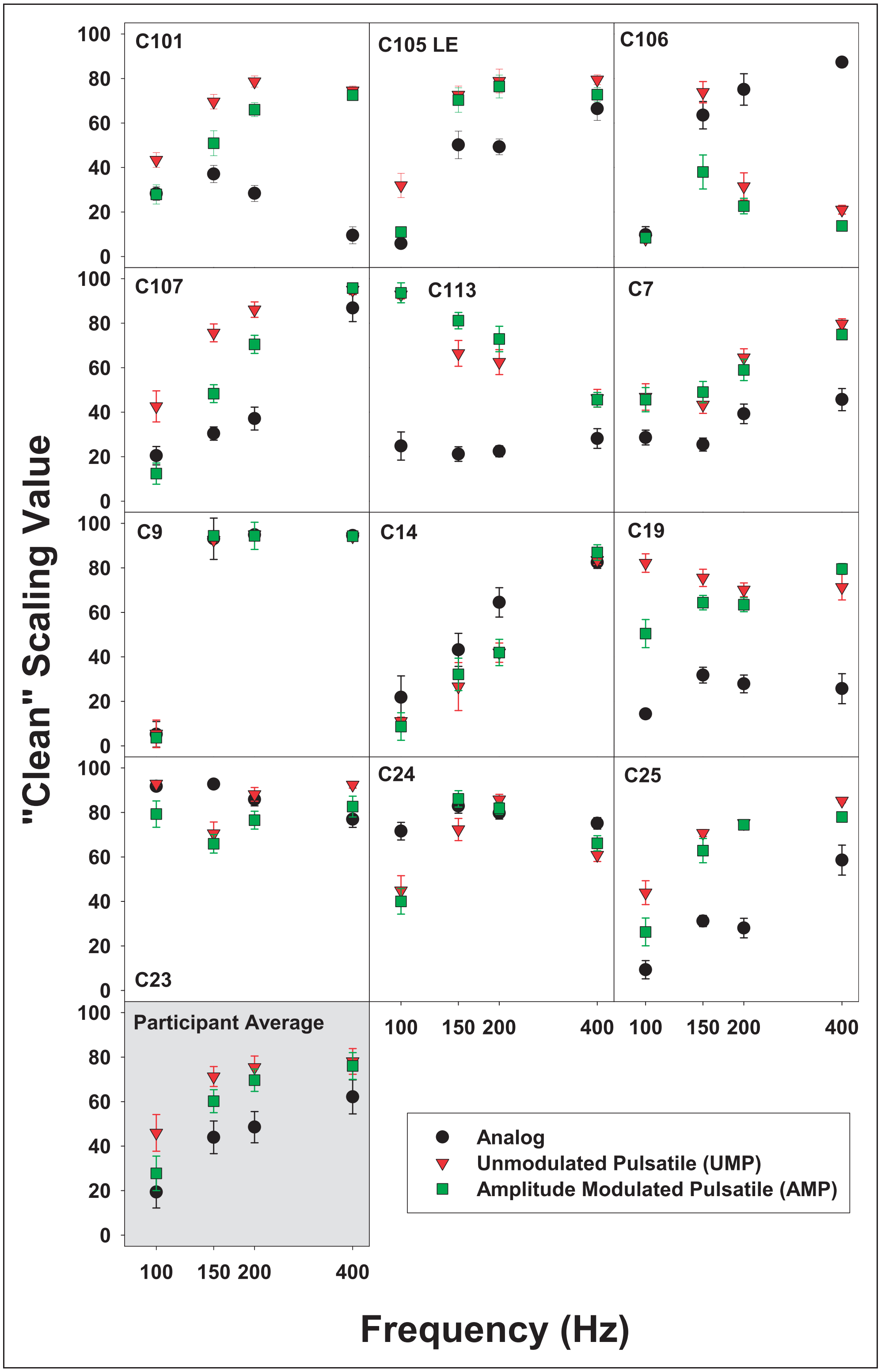

Figure 5. Scatter plot of scaled values in response to the question "How Clean is the sound?" Points are plotted as a function of frequency. Black circles represent analog stimulation, upside-down red triangles represent UMP stimulation, and green squares represent AMP stimulation. The 12 boxes with white backgrounds represent results for individual participants. The box in the lower right-hand corner with the gray background represents the data averaged across all participants. Error bars represent ± 1 standard error of the mean.

interpreted as "more normal." If so, it may be that the pulsatile stimulation used in the participants' every day strategies would sound more Clean as the user becomes more experienced with the implant. However, no correlation was observed between duration of use and the Clean ratings for the analog ($r = -0.170$, $n = 12$, $p = .598$), AMP ($r = 0.036$, $n = 12$, $p = .911$), or UMP ($r = 0.071$, $n = 12$, $p = .826$) stimuli. Similarly, no correlation was observed between duration of use and the difference in Clean ratings between analog and AMP stimuli ($r = -0.168$, $n = 12$, $p = .601$), analog and UMP ($r = -0.186$, $n = 12$, $p = .563$), or AMP and UMP ($r = -0.065$, $n = 12$, $p = .842$).

Discussion

In Experiments 1A and 1B, it was observed that the perceptual differences between pulsatile stimulation and analog stimulation were much larger than the perceptual differences between the two types of pulsatile stimulation (AMP and UMP). One potential explanation for the difference is that between pulses in pulsatile stimulation, there is a relatively large interpulse gap where no stimulation is provided. By contrast, analog stimulation provides a continuous waveform such that there are no gaps in time without stimulation. If the interpulse intervals are responsible for the sound quality differences between pulsatile and analog stimulation, then increasing the carrier rate (and reducing the interpulse interval) of AMP stimulation should reduce the perceptual differences between analog and AMP stimulation. This was investigated in Experiment 2A.

Experiment 2A—Multidimensional Scaling of Analog and AMP Stimuli With Various Carrier Rates

Methods

An MDS protocol was used as described earlier to evaluate two different stimulus sets. The first stimulus set consisted of 100-Hz analog stimulation and 100-Hz AMP stimulation with carrier rates at 750, 1,500, 3,000, 6,000, and 12,000 pps. The second stimulus set consisted of 400-Hz analog stimulation and 400-Hz AMP stimulation with carrier rates at 1,500, 3,000, 6,000, and 12,000 pps. 100-Hz and 400-Hz modulation rates were selected to represent the range of modulation rates used in Experiment 1. There was no specific hypothesis about perceptual differences between carrier rates for either modulation frequency. The 100-Hz and 400-Hz stimuli were run in separate blocks.

Results

The perceptual distance between 100-Hz analog and 100-Hz AMP stimuli with varying carrier rates (750, 1,500, 3,000, 6,000, or 12,000 pps) were averaged across participants. An ALSCAL analysis was used to map the perceptual space from the averaged data for 100 Hz onto two dimensions as illustrated in the left panel of Figure 6. Similarly, the perceptual distance between 400-Hz analog and 400-Hz AMP stimuli with varying carrier rates (1,500, 3,000, 6,000, or 12,000 pps) were averaged across participants, and an ALSCAL analysis mapped the perceptual space into two dimensions as illustrated

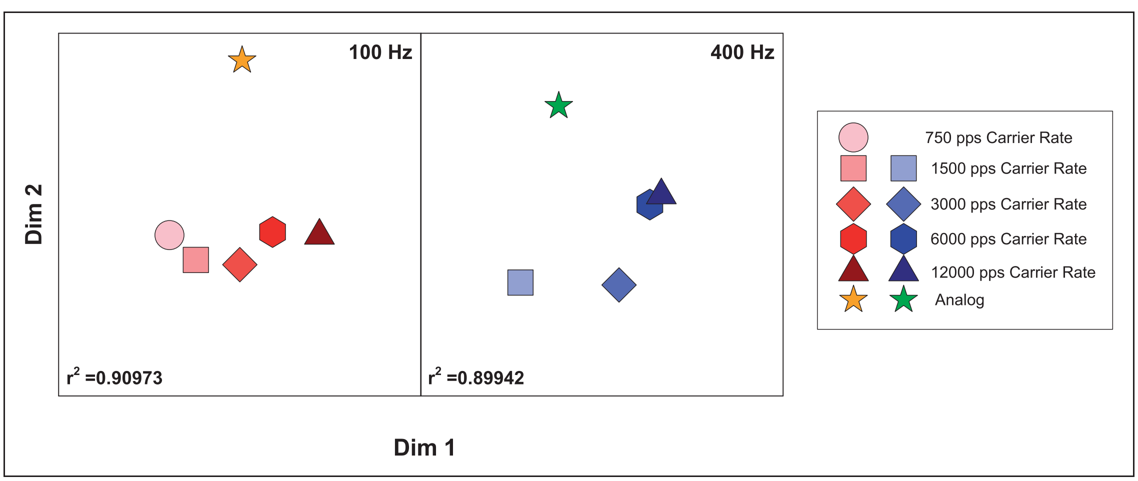

Figure 6. Multidimensional scaling results averaged across all participants tested in Experiment 2A plotted in two dimensions. Results for 100-Hz stimuli are plotted in the left panel, and results for 400-Hz stimuli are plotted in the right panel. The r^2 representing the goodness of the fit is presented in the lower left corner of each plot. Stars indicate the position of the analog stimulus, while the remaining symbols indicate the positions of the AMP stimuli at different carrier rates (see figure legend). Note that for the AMP stimulation, increased saturation of the color for each symbol indicates an increased carrier rate.

in the right panel of Figure 6. The r^2 representing the goodness of fit is 0.91 for the 100-Hz stimuli and 0.90 for the 400-Hz stimuli suggesting that the two-dimensional space accurately describes the perceptual relationships between the stimuli for both data sets. It appears that for both 100-Hz and 400-Hz AMP stimuli, a single dimension represented the perceptual change associated with a change in stimulation rate. For the 100-Hz stimuli, the differences in carrier rates were described by Dimension 1. However, the difference between analog and pulsatile stimulation was primarily described by the second dimension, suggesting that for 100 Hz, the perceptual differences between analog and AMP cannot be explained by a change in carrier rate alone. For the 400-Hz stimuli, the perceptual differences due to carrier rate lay on a curve. A one-dimensional space is often represented by MDS as a curve as participants are likely to overestimate small perceptual differences and underestimate larger perceptual differences (e.g., Kendall, 1971; Landsberger et al., 2014; McDermott, & Clark, 1996; Mckay, McDermott, & Clark, 1996; Klawitter, Landsberger, Buchner, & Nogueira, 2018; Vermeire, Landsberger, Schleich, & Van de Heyning, 2013). For a detailed explanation of single-dimensional data represented by a curve using MDS, please see Hill and Gauch (1980), Wartenberg, Ferson, and Rohlf (1987), Diaconis, Goel, and Holmes (2008), or de Leeuw (2007). The analog stimulus does not lie along the curve defined by the different carrier rates of 400-Hz AMP stimuli, suggesting that for 400 Hz, the perceptual differences between analog and AMP cannot be explained by a change in carrier rate. It is unknown why the results for the 100-Hz AMP stimuli are arranged in a line, while those for the 400-Hz AMP stimuli are arranged in a curve.

The distances from analog stimulation to AMP stimulation for each of the tested modulation rates and carrier frequencies are presented in Figure 7. For the 100-Hz stimuli, the distance between analog and AMP stimuli was approximately constant across carrier rates. We fit the 100-Hz data to a mixed-effects regression model with carrier rate as a fixed effect and random intercepts for participants to determine if an increase in carrier rate resulted in AMP stimulation sounding more similar to analog stimulation. Models with and without carrier rate were compared using an F test. The model with carrier rate did not provide a significantly better fit than the model without carrier rate for the 100-Hz data, $F(1, 47) = 2.87$, $p = .097$. However, for the 400-Hz data, the distance between the analog and AMP stimuli seems to be reduced with an increase in carrier rate for the AMP stimuli. We fit the 400-Hz data to a mixed-effects regression model with carrier rate as a fixed effect and random intercepts for participants to determine if an increase in carrier rate resulted in AMP stimulation sounding more similar to analog stimulation. Models with and without carrier rate were compared using an F test. The model with carrier rate did provide a significantly better fit than the model without carrier rate for the 400-Hz data, $F(1, 35) = 6.27$, $p = .015$.

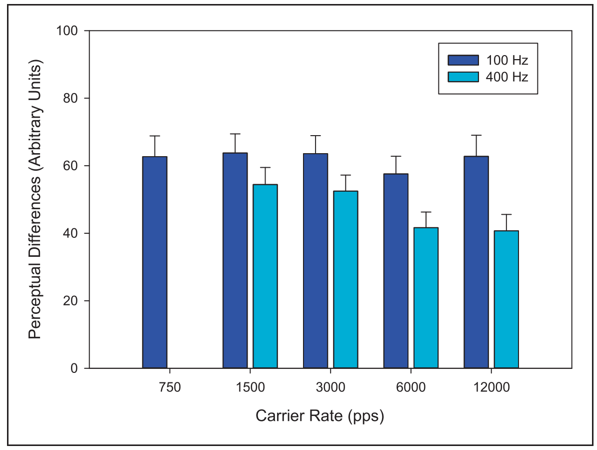

Figure 7. Bar plot showing the perceptual distance in Experiment 2A between analog stimulation and AMP stimulation with varying carrier rates. The 100-Hz frequency data are plotted in dark blue, and 400-Hz frequency data are plotted in light blue. Error bars represent $\pm$ 1 standard error of the mean.

Discussion

One potential explanation for the sound quality differences between analog and pulsatile stimulation is that analog stimulation consists of a continuous waveform, while pulsatile stimulation consists of pulses of relatively short durations interleaved with relatively long interpulse gaps without any stimulation. If so, reducing the interpulse gaps by increasing the stimulation rate for AMP stimulation should make the sound quality of AMP stimulation more similar to analog stimulation. Both 100- and 400-Hz AMP stimuli (Figure 6) are arranged in a continuum defining a single dimension which presumably represent carrier rate. In both the 100-Hz and 400-Hz MDS plots, the perceptual differences between analog and pulsatile stimulation are represented by a dimension that is orthogonal to the one defined by carrier rate. This suggests that there are perceptual differences between analog and pulsatile stimulation that are not produced by the lack of stimulation during the interpulse gaps. However, for 400-Hz (but not 100-Hz) AMP stimulation, higher carrier rates produce a sound that is somewhat more similar to analog than lower carrier rates. Although the interpulse gap is not the primary perceptual difference (as evidenced by the orthogonal dimension in Figure 6), the presence of an interpulse gap may play some role in the perceptual differences between analog and pulsatile stimulation.

Experiment 2B—Sound Quality Scaling of Analog and AMP Stimuli With Various Carrier Rates

Methods

In Experiment 2B, qualities of analog and AMP stimuli with various carrier rates were perceptually scaled according to how Clean or High they were using the previously described protocol. These data were collected to provide insight into the nature of the perceptual changes provided by the changing carrier rate. The stimulus set for Experiment 2B consisted of all of the stimuli from Experiment 2A. Specifically, 100 Hz was presented with AMP stimulation at 750, 1,500, 3,000, 6,000 and 12,000 pps, while 400 Hz was presented with AMP stimulation at 1,500, 3,000, 6,000, and 12,000 pps. In addition, analog stimulation at 100 Hz and 400 Hz were included in the stimulus set. Unlike in Experiment 2A, in a given block, both 100-Hz and 400-Hz stimuli were presented.

Results

The average pitch-scaled values were calculated for each carrier rate and analog stimulation at both 100-Hz and 400-Hz frequencies. The results averaged across all participants are presented in the large panel in the left side of Figure 8. The average plot indicates that 400-Hz AMP (blue) was perceived as higher than 100-Hz AMP (red) regardless of carrier rate. However, for all AMP stimuli with a given modulation rate, pitch height scaling did not seem to depend on carrier rate. Consistent with these observations, a two-way repeated measures ANOVA detected a main effect of modulation frequency, $F(1, 33) = 28.241$, $p < .001$, but did not detect an effect of carrier rate, $F(3, 33) = 0.865$, $p = .469$. An interaction between modulation rate and carrier rate was also detected, $F(3, 33) = 6.110$, $p = .002$. As 750-pps carrier data could only be collected with 100-Hz AMP, it was excluded from the analysis. Pitch scaling with analog stimulation yielded similar results to pitch scaling with AMP stimulation. That is, 100-Hz analog stimulation was pitch scaled similarly to 100-Hz AMP and 400-Hz analog stimulation was pitch scaled similarly to 400-Hz AMP. A two-way repeated measures ANOVA comparing analog and AMP stimulation averaged across carrier rates found a main effect of frequency, $F(1, 11) = 16.716$, $p = .002$, but no main effect for the difference between the pitch scaling for analog and AMP averaged across carrier rates, $F(1, 11) = 0.053$, $p = .822$. No interaction was detected, $F(1, 11) = 0.002$, $p = .963$. As the initial hypothesis was that lower carrier rates would sound less similar to analog stimulation than higher carrier rates, a two-way repeated measure ANOVA was also conducted comparing the pitch scaling of analog stimulation to

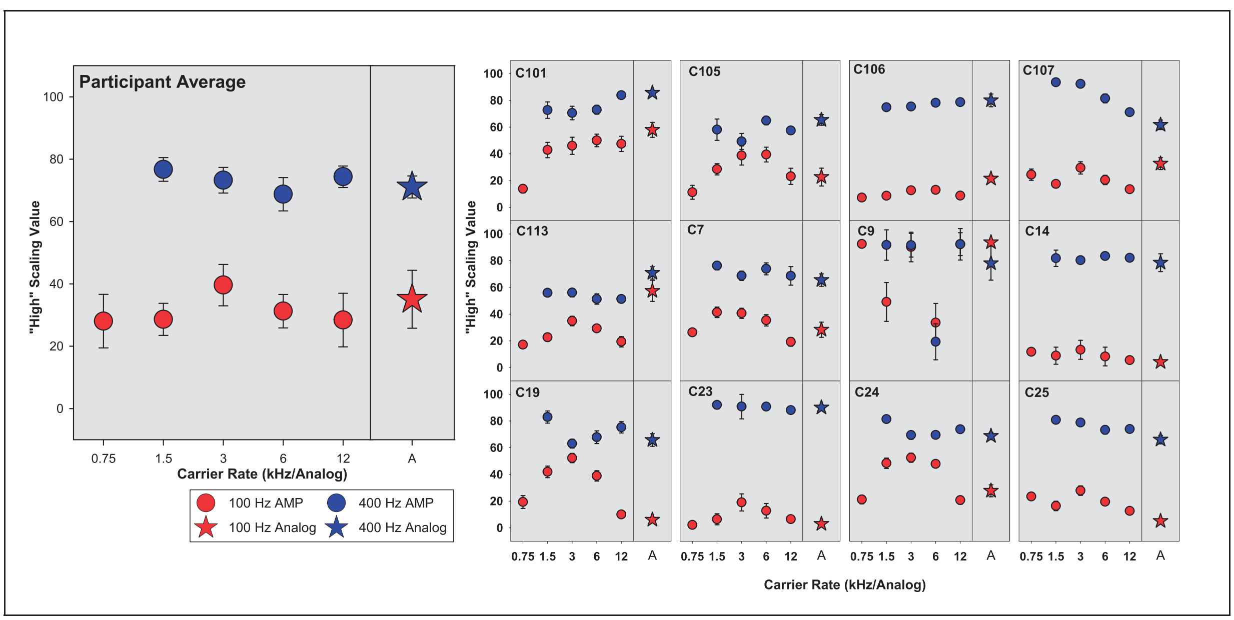

Figure 8. Scatter plot of scaled values in response to the question "How High is the sound?" for data collected in Experiment 2B. Data averaged across all participants are presented in the larger panel on the left. Individual results are presented in the 12 smaller panels on the right. Blue points indicate scaling data for 400-Hz stimulation, and red points indicate scaling data for 100-Hz stimulation. Stars indicate values for analog stimulation, while circles indicate values for AMP stimulation. Error bars represent $\pm$ 1 standard error of the mean. AMP = amplitude-modulated pulse trains.

pitch scaling with AMP simulation at 1,500 pps, which was the lowest carrier rate used for both 100- and 400-Hz modulations. Similarly, no main effect was observed between the pitch scaling for analog and AMP modulation with 1,500-pps carrier, $F(1, 11) = 0.009$, $p = .925$. A main effect of frequency was observed, $F(1, 11) = 24.853$, $p < .001$. No interaction was detected, $F(1, 11) = 2.847$, $p = .120$.

The results for each individual participant are shown in the smaller panels on the right side of Figure 8. The individual patterns typically resemble the average pattern. With the exception of C9, both AMP and analog stimulation at 100 Hz was always scaled as lower than 400 Hz. For most participants, analog stimulation at a given rate was pitch scaled similarly to AMP stimulation at the corresponding modulation rate. However, there were some notable exceptions. For example, C113 tended to rate analog stimulation as higher pitched than AMP stimulation, while C106 tended to rate the pitch difference between analog stimuli as smaller than the pitch difference between AMP stimuli. Although no effect of carrier rate was observed on average, for a number of participants (e.g., C105, C113, C7, C19, C23, and C24), the lowest and highest carrier rates were rated as lower in pitch than the middle carrier rates for 100 Hz.

The average Clean-scaled values were calculated for each carrier rate and analog stimulation for both 100-Hz and 400-Hz stimulation. The results averaged across all participants are presented in the large panel in the left side of Figure 9. The average plot indicates that 400-Hz AMP (blue) was perceived as Cleaner than 100-Hz AMP (red) regardless of carrier rate. However, for a given modulation frequency, the Cleanness seemed to vary with carrier rate. A two-way repeated measures ANOVA on the Clean scaling of the AMP data detected main effects of modulation frequency, $F(1, 33) = 12.225$, $p = .005$, and carrier rate, $F(3, 33) = 5.486$, $p = .004$, as well as the interaction, $F(3, 33) = 3.968$, $p = .016$. Again, as 750-pps carrier data could only be collected with 100-Hz AMP, it was excluded from the analysis. The main effect of carrier rate likely reflects the pattern observed that the lowest and highest carrier rates for 100-Hz modulations were rated as less Clean than the middle carrier rates. Clean scaling with analog stimulation yielded similar results to Clean scaling with AMP stimulation. That is, 100-Hz analog stimulation was Clean scaled similarly to 100-Hz AMP and 400-Hz analog stimulation was Clean scaled similarly to 400-Hz AMP. A two-way repeated measures ANOVA comparing analog and AMP stimulation averaged across carrier rates found a main effect of frequency, $F(1, 11) = 18.765$, $p = .001$, but no main effect for the difference between the Clean scaling for analog and AMP averaged across carrier rates, $F(1, 11) = 1.552$, $p = .239$. No interaction was detected, $F(1, 11) = 0.0333$, $p = .859$. As the

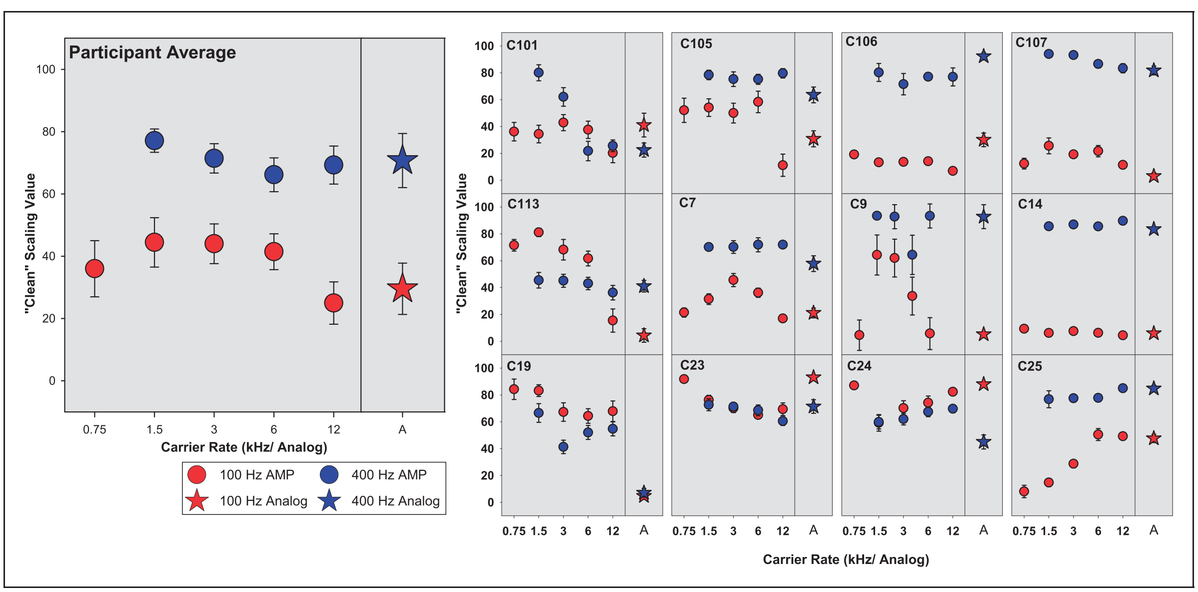

Figure 9. Scatter plot of scaled values in response to the question "How Clean is the sound?" for data collected in Experiment 2B. Data averaged across all participants are presented in the larger panel on the left. Individual results are presented in the 12 smaller panels on the right. Blue points indicate scaling data for 400-Hz stimulation, and red points indicate scaling data for 100-Hz stimulation. Stars indicate values for analog stimulation, while circles indicate values for AMP stimulation. Error bars represent ± 1 standard error of the mean. AMP = amplitude-modulated pulse trains.

initial hypothesis was that lower carrier rates would sound less similar to analog stimulation than higher carrier rates, a two-way repeated measures ANOVA was also conducted comparing the Clean scaling of analog stimulation to Clean scaling with AMP stimulation at 1,500 pps, which was the lowest carrier rate used for both 100-Hz and 400-Hz AMP modulations. No main effect of stimulation type was detected, $F(1, 11) = 4.771$, $p = .051$. A main effect of frequency, $F(1, 11) = 15.187$, $p = .002$, was detected. No interaction was detected, $F(1, 11) = 0.242$, $p = .663$.

The results for each individual participant were shown in the smaller panels on the right side of Figure 9. The results from individual participants appeared to vary more than for the pitch scaling task. For some participants, Clean ratings were primarily dependent on frequency (e.g., C106, C107, and C14). For other participants, Clean ratings seemed to vary with both frequency and carrier rate (e.g., C101, C113, C9, and C19). However, while the majority of participants rated higher frequencies as Cleaner than lower frequencies, there were a number of exceptions (e.g., C19, C24, and possibly C23). In addition, analog stimulation was generally rated as similarly Clean to AMP stimulation. However, there were a number of notable exceptions. For example, C19 rated analog stimulation much less Clean than AMP stimulation regardless of rate. C24 scaled analog stimulation at 400 Hz as less Clean than AMP stimulation.

Discussion

While a perceptual dimension related to carrier rate was observed in Experiment 2A (Figure 6) for both 100-Hz and 400-Hz AMP stimulation, the perceptual quality associated with this change is unclear. Neither Clean nor High scaling showed a consistent change for these stimuli as a function of carrier rate (Figures 8 and 9). It appears that the lowest (750 Hz) and highest (12,000 Hz) produce a lower value for Clean scaling than the other carrier rates although the explanation for this observation is unclear. Although rate pitch typically saturates at about 300 Hz (e.g., Carlyon, Deeks, & McKay, 2010; Eddington et al., 1978; Mladejovsky, Eddington, Dobelle, & Brackmann, 1975; Shannon, 1983), other studies have reported that subjects can discriminate stimuli at much higher baseline rates. Landsberger and McKay (2005) demonstrated that subjects can often discriminate rates up to 12,800 Hz without modulations, although the perceptual quality used to make these judgments was unclear. When asked to pitch rank discriminable high-rate pulse trains, the higher rate stimuli were sometimes reported as higher, sometimes reported as lower, and sometimes no consistent pitch ranking was observed. This suggests that at high rates, pitch was not a reliable explanation for the perceptual differences between higher rates of stimulation. Nevertheless, Goldsworthy and Shannon (2014) were able to train listeners to pitch rank higher rates of stimulation (up to 3520 Hz) correctly. Further study is needed to understand the perceptual changes produced by a change in carrier rate.

General Discussion

In this study, we investigated the perceptual differences between analog and pulsatile stimuli to get a better understanding for why some cochlear-implant users prefer analog to pulsatile stimulation. The results of Experiment 1A (Figure 2) show that a change in stimulation frequency can be described by a single dimension for analog and pulsatile stimulation. This suggests that the perceptual quality associated with a change in rate is similar for each of the stimulation types. Therefore, the preferences of some users for analog stimulation are likely not to be related to how rate pitch is encoded with analog and pulsatile stimulation. Figure 4 shows an increase in pitch height as a function of frequency for all stimulation types. If the auditory nerve were to respond to both the cathodic and anodic phases of analog stimulation, it might be expected that it would fire once per phase (twice per period) producing a pitch percept approximately double of that reported for pulsatile stimulation at the same frequency. However, at a given frequency, all stimulation types are rated as having a similar pitch. Distinction on the basis of stimulus frequency is to be expected because most cochlear-implant listeners are able to distinguish stimulus frequency for analog and pulsatile stimuli up to about 300 to 400 Hz (Carlyon et al., 2010; Eddington et al., 1978; Mladejovsky et al., 1975; Shannon, 1983). For some listeners, the "pitch saturation frequency" has been reported to be as high as 1 to 2 kHz (Bilger & Black, 1977; Hochmair-Desoyer et al., 1981; Hochmair-Desoyer, Hochmair, Burian, & Stiglbrunner, 1983).

An increase in rate was also described as an increase in how Clean the stimulation sounded (Figure 5). Landsberger et al. (2016) found a similar pattern (i.e., an increase of rate was described as being more Clean) at a similar cochlear location for users of 31-mm MED-EL electrode arrays (Electrode 5; Landsberger et al., 2015; Vermeire et al., 2008). Similarly, Fearn and Wolfe (2000) found that Electrode 22 of Nucleus straight arrays (also at a similar insertion depth; Landsberger et al., 2015) were described as increasing in "desirable quality" as a function of stimulation rate over the range of 100 to 400 pps. Although the sound-quality ratings of different stimulation frequencies in Landsberger et al. (2016) and Fearn and Wolfe (2000) were both measured only with pulsatile stimulation, a similar pattern was observed in the present experiment using analog stimulation. It is worth noting that Landsberger et al. (2016) found consistently high ratings for low rates of stimulation only for contacts inserted well into the second cochlear turn. It is therefore plausible that the effect of rate on Clean scaling with analog stimulation observed in the present experiment may be cochlear-location dependent.

Although analog and pulsatile stimulation seem to encode frequency in a similar manner, a sizeable perceptual difference between analog and pulsatile stimulation was observed. That is, in the MDS scaling of Experiment 1A, a dimension independent of frequency described the perceptual differences between analog and pulsatile stimulation (Figure 2). The two different pulsatile stimulation types (AMP and UMP) were close to each other in the MDS plot suggesting that encoding the same frequency with an equal-amplitude pulse train (UMP) or an AMP with a deep modulation depth sound very similar. It is worth noting that from the current data, it is impossible to determine from Figure 2 if the two stimulation types sounded identical or if there were small but distinct perceptual differences between the two types of stimulation. The summary of perceptual distance between the various stimulation types (Figure 3) illustrates that the perceptual differences between analog and pulsatile stimulation were larger at lower frequencies.

While the MDS analysis indicates that there was a large perceptual difference between analog and pulsatile stimulation, it did not provide information about the nature of the perceptual differences. The perceptual difference between analog and pulsatile stimulation was likely not to be related to pitch as no main effect of stimulation type with a pitch scaling task (Figure 4) was observed. However, the perceptual differences between the stimulation types may be described by how Clean they were as a main effect of stimulation type was observed on a Clean scaling task (Figure 5). While the majority of participants scaled analog stimulation as less Clean than pulsatile stimulation, there were some participants (e.g., C9 or C24) who similarly ranked analog and pulsatile stimulation, while other participants (e.g., C14 and C106) tended to rank analog as being more Clean than pulsatile stimulation. These differences across participants were not surprising in that preference for analog or pulsatile strategies also varied across participants in previous studies (e.g., Battmer et al., 1999, 2000; Osberger & Fischer, 1999, 2000). While in designing the experiment we had assumed that Clean would be a positive attribute of a sound, this may not be the case. Battmer et al. (2000) suggested that for those who preferred an analog strategy, although there was more background noise associated with analog stimulation, there also seemed to be more information and a more pleasing sound quality than with a pulsatile stimulation. It is therefore possible that stimulation with the more "noisy" pattern might yield preferable results than a Clean pattern for some individuals. It is worth noting that Landsberger et al. (2016) found that if a pulse train was rated as noisy then it was also rated as not Clean. Conversely, if a pulse train was rated as Clean, it was also rated as not noisy. It might be that our analog stimulation that is rated as less Clean would yield a more desirable sound quality in an analog stimulation strategy. It may also be that Clean (or any single adjective) is not sufficient to capture preference, particularly given that preference to analog stimulation in the study by Battmer et al. (1999) was associated with "deeper" sounds. The everyday experience of our participants with pulsatile stimulation might also have biased their judgment such that Clean was interpreted as "more normal."

In most of the previous studies comparing preference of analog and pulsatile stimulation (e.g., Battmer et al., 1999; Osberger & Fisher, 1999), participants were recent implantees. It would be interesting to determine to what extent cochlear-implant experience would affect ratings of adjectives describing timbre.

One limitation is that it is difficult to determine exactly what the term Clean indicates as the term is subjective and was not formally defined by the experimenters for the participants. In previous studies, cochlear-implant users described stimulation with a narrower spread of excitation as being more Clean than stimulation with a broader spread of excitation (Landsberger et al., 2012; Padilla & Landsberger, 2016). It may therefore be that analog stimulation provides a broader spread of excitation than pulsatile stimulation. In addition, Clean stimulation has been reported as corresponding to higher rates or more apical stimulation locations (Landsberger et al., 2016 as well as the present study). Although the perceptual scaling of Clean and High provides some insight into the perceptual differences between analog and pulsatile stimulation, further studies are needed to attain a better understanding of the nature of the perceptual differences.

Our quantitative findings contrast with the qualitative findings from Eddington et al. (1978) who found that participants could not distinguish between sinusoidal and pulsatile stimuli when they were matched for loudness and pitch. Michelson (1971), however, also reported timbral differences between sinusoidal and pulsatile stimulation. In our MDS task, each participant was presented with each pair of stimuli multiple times and we balanced only for loudness. Because we did not predefine perceptual dimensions or qualities associated with the stimuli, participants simply quantified how different two stimuli were and were not required to evaluate pitch and timbre separately—percepts that are often confused (Houtsma, 1997). In contrast, in the study by Eddington et al., participants were required to match both the loudness and pitch of stimuli, presumably by changing the amplitude and frequency of one of the stimuli, before being asked to describe timbre differences. Changing amplitude and frequency will affect loudness, pitch, and timbre because of the complex interaction of these parameters. Participants may have resorted to making the stimuli as perceptually similar as possible, thus reducing differences in timbre rather than pitch alone.

In Experiments 2A and 2B, we have established that there are perceptual differences between analog and amplitude-modulated pulsatile stimulation that cannot be accounted for by the rate of the carrier frequency. The underlying physiological causes, however, of perceptual differences between analog and pulsatile stimulation are still unclear. For both sinusoidal and pulsatile stimuli, cochlear-nerve fibers would be expected to strongly phase lock to the low frequencies used in this study (Hartmann, Topp, & Klinke, 1984; Parkins, 1989;van den Honert & Stypulkowski, 1987), and so provide pitch information from interspike intervals (e.g., Evans, 1978). For frequencies up to about 500 Hz, auditory nerve fibers are expected to fire once per period at high intensities (e.g., van den Honert & Stypulkowski, 1987). Some studies have found multiple action potentials in response to a single period of low-frequency sinusoidal stimulation (e.g., Parkins, 1989; van den Honert & Stypulkowski, 1987), but if that were the case, here we might have expected to have found different pitches across the pulsatile and sinusoidal stimuli. It may be that for equal loudness, the differences in timbre arise because the most excited nerve fibers (i.e., those closest to the stimulating electrode) are not saturated for either sinusoidal or pulsatile stimulation and the interval histograms for these fibers differ. That is while the spike intervals are around integer multiples of the period, the proportion of spikes at each interval differ. Alternatively, fibers closest to the electrode may be saturated and timbre differences may depend on the spike intervals of more distant fibers. While it is known that single interval histograms for pulsatile and sinusoidal stimuli can differ, and there is typically greater synchronization to pulsatile stimulation than to sinusoidal stimulation (Hartmann et al., 1984; van den Honert & Stypulkowski, 1987), the population response of the auditory nerve to sinusoidal and pulsatile electrical stimulation is currently unknown. Nonetheless, if the timbre is dependent on the response of distant fibers, then stimulation of multiple electrodes with the same sinusoidal or pulsatile stimulus might be expected to result in more similar timbres.

Conclusions

Using both multi- and single-dimensional scaling techniques, we have verified that the perceptual quality of analog and pulsatile stimulation is considerably different from each other. The differences do not appear to be related to pitch height. A follow-up experiment determined that the perceptual difference between analog and pulsatile stimulation cannot be completely explained by the presence of an interpulse interval in the pulsatile stimuli. These results are consistent with numerous clinical reports that analog and pulsatile cochlear implant sound processing strategies have noticeably different sound qualities. However, further research is needed to understand the underlying causes of these perceptual differences.

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