



Research paper

Psychometric function of jittered rate pitch discrimination



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ABSTRACT

The impact of jitter on rate pitch discrimination (JRPD) is still a matter of debate. Previous studies have used adaptive procedures to assess pitch discrimination abilities of jittered rate pulses (Dobie and Dillier, 1985; Chen et al., 2005) or have used jitter detection thresholds (Fearn, 2001). Previous studies were conducted in a relatively small number of subjects using either a single-electrode cochlear implant (Dobie and Dillier, 1985, $n = 2$) or the Nucleus multi-channel devices (Fearn, 2001, $n = 3$; Chen et al., 2005, $n = 5$). The successful application of an adaptive procedure requires a monotone psychometric function to achieve asymptotic results. The underlying psychometric function of rate jitter has not been investigated so far. In order to close this knowledge gap, the present study determines psychometric functions by measuring of JRPD with a fixed stimulus paradigm. A rather large range of temporal, Gaussian distributed jitter standard deviation 0, 1, 2, 3, 4 ms was applied to electrical pulse patterns. Since the shape of the underlying probability density function (PDF) may also effect JRPD, a uniform PDF was alternatively applied. 7 CI users (8 ears, high-level performers with open-speech perception, MED-EL Pulsar/Sonata devices, Innsbruck, Austria) served as subjects for the experiment. JRPD was assessed with a two-stage forced choice procedure. Gross results showed decreasing JRPD with increasing amounts of jitter independent of the applied jitter distribution. In conclusion, pulse rate jitter affects JRPD and therefore should be considered in current coding strategies.

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1. Introduction

1.1. Pitch discrimination in electrical hearing

Rate pitch discrimination in electrical stimulation has been intensively studied in the past (e.g. Dobie and Dillier, 1985; Townshend et al., 1987; McDermott and McKay, 1997; Rubinstein et al., 1999; McKay et al., 2000; Zeng, 2002; Wieringen et al., 2003; Litvak et al., 2003; Baumann and Nobbe, 2004; Chen et al., 2005; Kong et al., 2009; Bahmer and Baumann, 2013; Goldsworthy and Shannon, 2014). Results show that the just-noticeable difference in rate pitch (JNDR) with electrical hearing is poor compared to normal hearing and that it deteriorates especially with pulse rates higher than 300 pulses per second (pps). Large variability in JNDR across subjects has also been reported. For example, at a base rate of 200 pps, JNDRs range from 5.4% (McDermott and McKay, 1997) to 50% (Townshend et al., 1987). There are several concepts concerned with the improvement of

pitch discrimination in general (not restricted to rate pitch), e.g. increasing the number of effective stimulation sites by introducing virtual channels (Donaldson et al., 2005; Koch et al., 2004) and current steering (Firszt et al., 2007), sharpening the spatial spread of excitation by introducing tripolar pulse patterns (Kral et al., 1998; Bierer, 2007), or by the application of jitter on pulse pattern periodicity.

The underlying idea of introducing jitter is to potentially overcome the strong entrainment of nerve fibers' activity to electrical stimulation. In normal hearing, according to the volley theory of Wever and Bray (1930a, c, b) and the combined resonance-volley theory (Wever, 1949), stochastic firing enables a transfer of rate pitch information even higher than 1 kHz, which corresponds to an absolute refractory period of about 300–400 μ s of auditory nerve fibers (Hughes et al., 2012; Morsnowski et al., 2006; Miller et al., 2001). Therefore, restoring physiologic stochastic firing by introducing jitter may improve rate pitch judgment (Morse and Evans, 1999; Rubinstein et al., 1999; Chen et al., 2005). The introduction of jitter has been evaluated in previous studies using different jitter probability distribution functions (PDFs). In order to motivate the implementation of a certain jitter distribution function, it is crucial to understand and describe the stochastic properties of spontaneous and stimulated activity of auditory nerve fibers.

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Even at low frequencies (e.g. 100 Hz) neurons do not always respond to every cycle of the stimulus; neurons skip cycles stochastically (Hartmann et al., 1984). Therefore, interval histograms consist of peaks corresponding to the values of integer multiples of the stimulus period. Nevertheless, a histogram showing the interspike intervals of the summed activity of several neural units can contain interval values as small as the stimulus period, even for stimulus frequencies higher than 1 kHz (volley theory of Wever and Bray (1930a,c,b) and combined resonance-volley theory (Wever, 1949)).

Neural activity as an action potential is often described by a discrete (values 0 and 1 in continuous time) Poisson-like distribution (Amit and Tsodyks, 1991; Tsodyks et al., 1998) (auditory nerve: Carney, 1993). However, when cats' auditory nerve fibers were stimulated with high-rate electrical pulse trains (5000 pps) which according to Rubinstein et al. (1999) should introduce Poisson-like distributed intervals, such a distribution could only be observed in about 25% of the fibers (Litvak et al., 2003). Therefore, it can be concluded that electrical stimulation of nerve fibers with high-rate frequency (5000 pps) does not restore the spontaneous behavior seen in normal hearing.

1.2. Relation of acoustical to electrical rate jitter

In normal hearing, the perceptual effects of jitter have been carried out for different kinds of stimuli (e.g. pulse trains) and jitter distributions (Pollak, 1968a,b; 1971). Compared to jittered pulse trains in electrical hearing, an acoustic pulse train consists of harmonics at multiples of F0 and results in an excitation pattern of the basilar membrane over a large frequency range (Fearn, 2001). A pulse from a single electrode stimulates only a restricted region although a certain spread of excitation is inherent. Also stronger phase-locking has been observed in electrical hearing rather than acoustic hearing (Hartmann et al., 1984; Dobie and Dillier, 1985). Therefore, results from acoustic experiments have to be carefully compared with results obtained in electrical hearing. The introduction of jitter to mimic stochastic nerve activity is still not able to fully restore normal activity as the temporal and spatial averages are different between the two modes of stimulation (ergodic principle, Dobie and Dillier (1985)). If only temporal information was jittered by stimulation (and not spatial information), the physiologic basis of acoustic hearing would only be matched in part, but could still potentially improve pitch estimation.

1.3. Previous studies on electrical rate jitter

Dobie and Dillier (1985) measured pitch discrimination and pitch difference detection in normal-hearing subjects and 2 single-channel cochlear implant recipients who were implanted with a ball contact in the round window niche. Pitch tasks were carried out using a two alternative forced-choice (2AFC) procedure applied in an adaptive way. One group of stimuli used in this study were pulse trains with jittered duration of intervals (base rate 80–1000 Hz). The interpulse intervals were Gaussian distributed with equal mean values and increasing standard deviations. Subjects had to detect which one out of two stimuli was jittered. For normal listeners, the standard deviation in jitter DL ranged from 0.18 to 0.01 ms with increasing rate (80–1 kHz). The two CI subjects perceived the jittered stimuli as being rough. Standard deviation in jitter DL ranged from 2.2 to 0.05 ms (at 80 Hz to 1 kHz base rate) and from 1.53 to 0.14 ms (at 125 Hz to 1 kHz base rate) for the two subjects.

The tested CI subjects showed an inferior performance to normal listeners which may be attributed to the pure temporal code provided by electrical stimulation. However, the comparison

of these results with present cochlear implant systems is questionable as the extra cochlear contact solely stimulated the basal neural structures of the spiral ganglion. In addition, the tested patients' neural survival was probably poor as they were deaf for a long time.

Chen et al. (2005) studied the effects of Gaussian jittered pulses (standard deviation 0.0, 0.1, 0.2, 0.3), "probalistic" pulses (see previous study), and auditory-model-generated pulses at mean base rates of 100, 250, 500, and 1000 Hz in three Nucleus-24 (Cochlear, Macquarie, Australia) cochlear implant recipients. Pitch discrimination was measured using a three-interval forced-choice (3IFC) adaptive procedure. Probalistic pulses were defined by the occurrence of a pulse in the pulse train as determined by a certain probability. Therefore, the interval between two consecutive pulses was a multiple of the period of a fixed-rate pulse train. The auditory-model-generated pulses were calculated using an auditory model incorporating a basilar membrane model (Lopez-Poveda and Meddis, 2001), gammatone filters, an inner hair cell model (Meddis, 1986), and an auditory nerve model (Carney, 1993). Overall, they observed no beneficial effect of any of the tested jitter distributions on rate pitch discrimination. With lower stimulation rate (125 and 250 Hz), a decrease in performance was also observed. They concluded that both "the right time and the right place" may be needed to restore normal pitch perception in cochlear-implant users. Their results suggest that introducing jitter does not lead to improved pitch perception.

Fearn (2001) studied CI recipients' ability to discriminate jittered pulse trains (verbal response "same" or "different") from unjittered pulse trains in five subjects. In contrast to the previously described study, Fearn did not investigate pitch discrimination. He addressed the amplitude, rate, and place dependence of jitter detection. The jitter detection threshold was defined as the point at which jitter was detected at a rate equal to 50% successful discrimination. Jitter thresholds were dependent on electrical stimulation rate. Jitter thresholds increased from low to high stimulation rate and the average detection rate was comparable to the results of Dobie and Dillier (1985).

1.4. Conclusions regarding previous studies and consequences

In order to assess JRPD, an adaptive procedure can be employed (Dobie and Dillier, 1985; Chen et al., 2005). For convergence to occur in an adaptive-forced choice experiment, the presence of a monotonic psychometric function is assumed, however, this has not yet been documented. Thus, it is important to determine individual psychometric functions that show an increase in JRPD depending on the amount of jitter. To our knowledge, no psychometric function has been recorded so far that shows the effect of jittered pulse rate on pitch discrimination. It is hypothesized that with increasing amounts of jitter pitch discrimination decreases because temporal information is hampered and the lack of regularity in temporal information degrades the saliency of temporal pitch in electrical hearing. As outlined above, previous studies have applied Gaussian probability density functions (PDFs). In order to evaluate effects related to PDF, in the present study both a Gaussian and a uniform PDF were implemented.

In summary, the aim of this study is the reproduction of previous results on jitter and enhancing the power of the study by

- increasing both the number of subjects as well as the individual performance level,
- employment of monopolar electrode configuration (nowadays commonly used),
- employment of rate pitch experienced users of cochlear implants,

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