A systematic review of the impact of adjusting input dynamic range (IDR), electrical threshold (T) level and rate of stimulation on speech perception ability in Cochlear Implant users.

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Acronyms:

CI – Cochlear Implant

ASC – Automatic Sensitivity Control

AGC – Automatic Gain Control

EDR – Electrical Dynamic Range

IDR – Input Dynamic Range

IIDR – Instantaneous Input Dynamic Range

A systematic review of the impact of adjusting input dynamic range (IDR), electrical threshold (T) level and rate of stimulation on speech perception ability in Cochlear Implant users.

Abstract:

Objective: To systematically review the evidence of how adjustments of the electrical T Level, Input Dynamic Range (IDR) and electrical stimulation rate impact on speech perception for cochlear implant (CI) users. *Design:* Systematic review. *Study sample:* A search of two electronic data sources yielded 32 studies, which met the inclusion criteria. A quality assessment and two evidence-based practice (EBP) review rating schemes were used to grade studies. *Results:* Due to the heterogeneity of speech perception measures, CI device type and study design, comparisons were made by structured review. *Conclusion:* The quality of studies was found to be moderate to poor. Increasing T levels above behavioural threshold, or as proportion of electrical dynamic range (EDR), has been demonstrated to improve perception of monosyllables in quiet and sentences in both quiet and in noise. Specific IIDR and IDR setting may improve perception of monosyllables in quiet and sentences in noise. However, no recommendation could be determined for setting rate of stimulation as speech perception varied significantly across rates examined. To optimise speech perception, a bespoke approach to parameter setting providing a individualised CI fitting is recommended; however, detail of how to optimise settings and the interactions between parameters is as yet unknown.

Keywords: Cochlear implants; Speech perception; Stimulation rate; Input Dynamic Range

Introduction:

Continuing development in signal processing techniques, changes in implant candidacy criteria and improved preservation of residual hearing have all contributed to better speech perception abilities in cochlear implant (CI) users (Balkany et al. 2007; Di Lella et al. 2010; Blamey et al. 2012). However, despite these reported improvements, a limitation remains for CI users when detecting speech presented at soft intensity levels or in the presence of noise (Donaldson et al. 2009; Boyle et al. 2013).

There are several programmable parameters which define how a CI delivers stimulation to the auditory system. Although not an exhaustive list, programmable parameters include the minimum and maximum electrical stimulation levels, the number of active stimulating electrodes, the range of acoustic information captured prior to electrical transduction and the overall rate of electrical stimulation. Setting these parameters is performed with the intention to ensure the electrical stimulation pattern generated by the CI provides optimal hearing benefit and speech perception. While the effect on speech perception of several changes to parameters have been evaluated (Gifford and Revitt 2010; Gifford et al. 2011; Holden et al. 2011; Spahr and Dorman 2005; Spahr et al. 2007) there has not yet been a systematic review of the effect of changing individual parameters and possible interactions between parameters on speech perception.

Vaerenburg et al. (2014) conducted a global survey of CI programming by collating the responses of 47 CI centres. They reported the results of an inventory of worldwide clinical programming practice for 2013-14, which revealed the most frequently adjusted programmable parameters for all four CI manufacturers, including Cochlear Ltd, Med-El, Advanced Bionics and Neurelec. The decision to change parameters was reported to be guided by the individual preference of CI centres, CI manufacturer defaults and the adjustable parameters available within each manufacturer's device fitting software. All centres focused

primarily on the adjustment of the minimum and maximum stimulating current level, which defines the electrical dynamic range (EDR). Reduction of the total number of stimulating electrodes was also a common parameter change, reported in approximately 10-15% of cases. Reasons provided for deactivation of electrodes included abnormal impedances, extracochlear location, non-auditory effects or noisy auditory perception. However, it was noted that electrodes were never reported to be disabled because of speech perception performance.

Within the Cochlear Ltd device, microphone input sensitivity can be set either as an automatic sensitivity control (ASC) or as fixed constant input sensitivity. ASC in the Cochlear Ltd device automatically adjusts the input sensitivity dependent upon estimates of the relative levels of speech and noise in the incoming signal, with the goal of enhancing the speech signal and the fixed constant allows a pre-set microphone sensitivity to be programmed. For the Med-El device, the parameters which affect input sensitivity were adjusted in 11-14% of cases; for the Advanced Bionics device, sensitivity was adjusted in 4% of cases and for users of the Neurelec device, sensitivity was never adjusted.

Vaerenburg et al. (2014) reported sensitivity to be adjusted infrequently in clinical practice and when consideration was given to adjustment of the number of stimulating electrodes, this was indicated to be unrelated to speech perception at least in clinical practice. Where adjustment of the number of stimulating electrodes has been explored in research (Bierer and Faulkner 2010; Zhou 2017; Noble et al. 2016), there remains no consensus regarding methodology. Therefore, adjustment to sensitivity and to the number of stimulating electrodes have been considered to fall outside the remit of this review and have been excluded.

This systematic review will explore the effects on speech perception ability of adjustment to the following three parameters: (i) the input dynamic range (IDR), the range of

acoustic sound levels that are mapped into the EDR; (ii) the electrical stimulation threshold (T) level, for each electrode, the level of electrical stimulation mapped to the lowest level of the IDR; (iii) the rate of electrical stimulation per electrode.

IDR and T level have been selected for review as these parameters are commonly adjusted at initial device activation and influence the processing of soft intensity sound toward the lower boundary of the EDR. Electrical stimulation rate has been selected, as this parameter can be adjusted across a wide range, but limited programming guidance about achieving an optimal setting for speech perception is available. Speech perception outcomes have been limited to clinical measures of speech perception, including vowel and consonant identification, monosyllabic word tests in quiet and in noise and open set sentence tests in quiet and in noise. The intention of the review is to determine clinical recommendations for CI programming.

Brief overview of CI signal processing:

While there are many common features within the signal processing approaches used by different commercial manufacturers of CI systems, there remain distinctions with system design rationale and implementation. Consequently, differences exist in the terminology used by CI manufacturers to describe such features and their application within respective clinical programming software.

Processing an acoustic input to an electrical output requires transduction of a large acoustic input range of approximately 90dB to a relatively narrow EDR, typically between 6dB to 15dB (Fu and Shannon, 2000). To achieve this, CI manufacturers use two methods: an automatic gain control (AGC) circuit, which applies non-linear compression to the acoustic input, and a sensitivity control, which adjusts the microphone input gain and can be applied in either a fixed or adaptive mode. These two methods can be applied either in isolation or in

combination prior to transformation from the acoustic to the electrical signal domain. The minimum level of acoustic input captured is approximately 25dB SPL, which is analogous to the noise floor of the electronic system. Potential exposure of the CI user to an audible noise floor is further limited using default first-fit parameters which are offered by all manufacturers and which are often supplemented with passive warnings within programming software. The maximum electrical output is limited for all CI manufacturers using output limiting compression. For Cochlear Ltd and Med-El, output compression will limit electrical stimulation at a perceptual level of loud, but comfortable, which is labelled as C level or maximum comfort level (MCL) and set within clinical software. For Advanced Bionics and Neurelec, the limit to electrical stimulation will occur at a perceptual comfort level or M level set within the clinical software, with an additional stimulus range programmed within the upper volume control range applied as a percentage increase of the entire EDR. Output limiting compression applies a very high compression ratio above a fixed or programmable value, preventing stimulation above this value. The use of output limiting compression prevents overstimulation and ensures electrical transduction of an optimal acoustic signal range for the presentation of speech sounds.

IDR refers to the range of acoustic input post-attenuation by either an automatic gain control (AGC) or an ASC circuit. Instantaneous input dynamic range (IIDR) refers to the range of short-term acoustic fluctuations, which are instantaneously captured without the application of AGC or ASC and this term is used as a descriptor only for devices produced by Cochlear Ltd. Despite differences in terminology and in position within the electrical circuit, IDR and IIDR fundamentally describe the size of the input acoustic signal. IIDR adjustment within the Cochlear Ltd system is achieved by setting T-SPL and C-SPL. Within the fitting software, T-SPL is the input sound pressure level (SPL) where the implant starts to stimulate at T-level and C-SPL the input SPL where output limiting compression starts. Studies

reporting IDR adjustment were conducted using the Advanced Bionics system where IDR is an adjustable parameter within the clinical fitting software. No studies reporting adjustment for the Med-El or Neurelec systems were found, as these both have a fixed IDR.

Manufacturer terminology for T level is consistent for all CI manufacturers, where this represents the threshold of electrical stimulation and the lowest level of the EDR. Of note however, Cochlear Ltd, Med-El and Neurelec do not provide electrical stimulation below the setting of T level in default settings offered within their respective clinical software. In contrast, the Advanced Bionics device continues electrical stimulation below the setting of T level, despite T level representing an electrical value corresponding to perceptual hearing threshold. Therefore, the stimulus is likely inaudible to a CI user, particularly where the audible hearing threshold is configured accurately.

Electrical stimulation rate can be adjusted within all commercial CI systems. Stimulation rate refers to the number of electrical pulses delivered to each electrical contact per second; affecting the coding of information in the time domain. Rate per contact is capped by the overall system update rate, which is divided to multiple electrical outputs, either directly to an active electrical contact or indirectly through use of virtual current steering.

Method:

The systematic review was conducted in accordance with guidance published by the Centre for Reviews and Dissemination (2009). The research question has been derived using the population, intervention, comparators, objectives and study design (PICOS) methodology.

PICOS question:

In CI users, are adjustments of IDR, T level and rate of electrical stimulation, compared to manufacturer defaults, effective in improving speech perception?

The literature search considered studies where changes were made to the programmable parameters of IDR, T level and stimulation rate with a speech perception outcome. To extract research publications for review, each parameter was searched in combination with both “Cochlear Implant” and “Speech perception”. The electronic databases searched included MEDLINE and EMBASE and the databases were searched from the start date for each database up until 2nd January 2016, without language restriction. Figure 1 indicates key words used in the search fields.

Figure 1.

Figure 2 provides a flow chart of the primary search and inclusion process. In the primary search 242 studies were identified; these were stratified into 112 studies describing T level setting, 12 studies describing IDR setting and 118 describing stimulation rate setting. Following review of the title and abstract, 197 studies were excluded. A total of 45 studies were reviewed in full and a further 13 were excluded as they failed to meet the following extended criteria:

- (1) an experimental study using human subjects; not an animal model
- (2) IDR, (T) level or stimulation rate a key independent variable in the experimental design
- (3) a standardised speech perception measurement used to define the outcome

Figure 2.

Rating of Quality Evidence:

Two evidence-based practice (EBP) review rating schemes were used to allocate levels of evidence scores to each of the studies (Tables 1-3). Firstly, using the criteria of the Oxford Centre for Evidence Based Medicine (OCEBM) Levels of Evidence (2011). The OCEBM (2011) methodology enables a heuristic or “rule of thumb” classification allowing clinicians

and patients to answer clinical questions quickly and without resorting to pre-appraised sources. OCEBM provide a hierarchy with five levels of evidence, ranked by strength of evidence from Level 1 (highest) to Level 5 (lowest). Determination of the level score for each study applies a series of clinical questions, which consider the effect of treatment including benefit, harm and overall utility. Secondly, using the criteria of Valente et al. (2006) which also provide a five-point scale from Level 1 (highest) to Level 5 (lowest) for ranking studies according to strength of evidence and stratifying studies according to where evidence was measured. If evidence was measured in the "real world" it is described as Effective (EV), whereas evidence was measured under "laboratory or ideal" conditions, it is described as Efficacy (EF).

To determine level of evidence scores, independent detailed analysis of each article in full text was performed by two researchers; the first author (T.B.N) and the final author (D.A.V.). Any disagreement between the score determined was resolved by consensus.

Study Quality assessment:

The quality of studies was assessed through review of the following criteria. Missing data were accounted for, an appropriate analysis of the data was performed, confounding factors were reported and controlled for, appropriate outcome measures and controls were used, a power calculation was performed, eligibility criteria were clearly specified and ethical approval was gained.

Figure 3.

Data synthesis:

Significant heterogeneity existed in the methodology and experimental design of the studies which fulfilled the review criteria. Studies were conducted in multiple centres, speech test

material was in five different languages, with the majority in a pre-recorded format except for a single study which used 'live' voice presentation.

The most common speech outcome measure was the CNC wordlist, which was used in 15 studies. Three studies used the Freiburg monosyllable test, 1 study used the NU-6 wordlist and 4 studies used non-standardised speech materials. Non-standard materials consisted of monosyllables presented in cocktail party noise, a disyllabic wordlist, a categorical speech perception task and a two-digit numerical perception task.

There was similar diversity using vowel and consonant perception tasks: of the 9 studies which utilised a specific vowel identification task (i.e. excluding vowel identification scores extracted from performance on the CNC wordlist), 7 used the /hVd/ context, 1 used the /bVb/ context and 1 used the /bVt/. Specific consonant identification tasks were used in 10 studies. There were 8 uses of the /aCa/ context, 2 uses of the /iCi/ context and 1 use of the /eCe/ and /uCu/ contexts. Further analysis of the consonant features of manner of articulation, place of articulation and voicing were reported in 4 studies.

Sentence based speech perception material consisted of 9 standardised tests and 2 non-standardised tests recorded in four different languages. Sentences in noise used 5 different noise types and varied delivery by using either (i) a fixed signal to noise ratio (SNR) (ii) an adaptive procedure where speech level was fixed, but noise level was varied to determine a SNR at which speech recognition is at 50% correct, denoted as the speech reception threshold (SRT₅₀).

Study characteristics and outcomes have been tabulated to enable comparison. Where statistical analysis has provided a test outcome of significance, results have been included. To enable quantification, a statistical outcome of large significance refers to $p < 0.001$, of medium significance refers to $p < 0.01$ and of small significance refers to $p < 0.05$.

Results:

The inclusion criteria were met by 32 papers. A single paper assessed both T level and IDR setting and as adjustment to these parameters was made separately and the speech perception measured independently, the speech perception outcome has been included for both the T level and IDR setting change. Tables 1 to 3 provide details of the characteristics of studies for each of the parameter subsets of T level, IDR and stimulation rate.

Table 1.

Table 2.

Table 3.

Quality of studies:

Studies had a median sample size of 10 and a range from 3 to 150. None contained a meta-analysis or were based on a randomised controlled trial (Figure 3). Only one study performed a power calculation and 36% of studies reported missing data. Reasons provided for missing data included being unavailable to complete all test sessions, withdrawal following side effects from the change in stimulation pattern or being functionally incapable of completing the speech test outcome measure. Subject selection criteria were well documented in 81% of studies, although confounding factors were either uncontrolled or only partially controlled in 25% of papers; a specific example of which was the accounting and controlling for aetiologies with a known neuro-degenerative component or with an abnormal cochlear anatomy. The method of statistical analysis varied widely across studies, precluding statistical comparison of data. For all studies, subjects served as their own control and in thirteen studies a crossover design was employed to assess and quantify experimental order and learning effects.

From the EBP rating schemes, 3 studies were rated as OCEBM level 2 due to the use of randomisation within their design, 26 studies achieved level 3 and 3 achieved level 4. Using the Valente rating scale, 31 studies were at level 3; 1 was at level 4 and 12 of the 32 provided 'real life' listening experience following the parameter change. On this basis, the quality of studies was determined to be moderate to poor.

Table 4.

T level adjustment:

Eight studies explored the impact of adjustment to measured T level. T level is the level of electrical stimulation mapped to the lowest level of the IDR and a behavioural response at the threshold of audible detection to an electrical stimulus. Recommended methods for setting T level differ across manufacturers and devices. However, the methods reported in the eight studies which examined a departure from default advice, followed the following four approaches:

- setting the T level higher than measured perceptual threshold, to a perceptual loudness rating between very soft to medium or barely audible to soft.
- setting T at 10% of the M level (M level representing the maximum programmed stimulus level and the upper limit of the EDR)
- setting T level at a percentage of the EDR.
- setting T level at 0 μ A

Monosyllable tests in quiet were reported in two studies. No significant change to monosyllable perception was reported when T level was set at 10% of M (Tanamati et al. 2005). A significant, but small improvement was reported for elevating T level to a loudness rating of very soft to medium (Skinner et al. 1999). Similarly, Skinner et al. (1999) also found

that this adjustment produced a significant, but small improvement in phoneme perception. Vowel and consonant perception reported in two studies indicated either no difference when comparing behavioural T, T at 10% of M or T at 0 μ A (Spahr and Dorman 2005) or a small significant improvement for vowels and consonants with T set to a higher value within the EDR (Fu and Shannon 2000). Sentences in quiet, reported in four studies, indicated no change for T at 10% of M or for T at 0 μ A (Boyd 2006; Spahr and Dorman 2005; Tanamati et al. 2005) and a medium and a large significant improvement for elevated T at levels corresponding to a perceptual loudness rating of very soft to medium for sentences presented at 70dB SPL and 50dB SPL respectively (Skinner et al. 1999). Sentences in noise, reported in three studies indicated no change (Spahr and Dorman 2005; Tanamati et al. 2005) for T at 10% of M or T at 0 μ A and a small significant improvement in perception (Zhou and Pfingst 2014) for a T level elevated as a percentage of the EDR.

IDR adjustment:

Eight studies reviewed the outcome of a change to IDR. No studies explored IDR adjustment for the Neurelec or Med-El devices. Neurelec use a fixed IDR of 75dB and Med-El a roving 55dB sound window, adapted by an AGC circuit. For studies using the Cochlear Ltd device, instantaneous input dynamic range or IIDR is reported, which for the current Cochlear N6 speech processor applies a default IIDR value of 40dB SPL. In Advanced Bionics devices, the default of 60dB IDR will capture acoustic signals from 25dB SPL to 85dB SPL. If the IDR is decreased this will restrict the acoustic input translated to the lower end of the electrical dynamic range, e.g. a 40dB IDR would correspond to acoustic levels between 45 and 85 dB SPL. Conversely, an increased IDR of 70dB would translate acoustic levels between 25 to 95 dB SPL to the electrical domain.

Monosyllable perception tests were reported in four studies. Holden et al. (2011) reported a medium significant improvement for an IDR of 65 and 80dB compared to 50dB and three studies which reported a large significant improvement in perception for an IIDR of 40dB compared to 30dB (Davidson et al. 2007; Holden 2007) and for 46dB and 56dB compared to 31dB (Dawson et al. 2007).

Phoneme perception showed a large significant improvement for an IIDR of 40dB compared to 30dB (Holden et al. 2007). Vowel perception was reported in four studies; Holden et al. (2007) and James et al. (2003) found no significant change, but Dawson et al. (2007) reported a large significant improvement in perception for an IIDR of 48dB and 56dB compared with an IIDR of 31dB. Zeng et al. (2002) reported a medium significant improvement for IDRs of 40, 50 and 60dB when compared to narrower levels. Of note, Zeng et al. (2002) presented vowels in speech shaped noise at +5dB SNR rather than in quiet. This was the only example of a study investigating IDR using a test condition with noise.

Consonant perception was reported in four studies. James et al. (2003) and Zeng et al. (2002) reported a medium significant improvement in perception when comparing an IIDR of 30dB to an IIDR of either 38dB or 41dB and for an IDR of 50dB and 60dB compared to an IDR of 40dB or less. A large significant improvement was reported for two studies which compared an IIDR of 46dB and 56dB with an IIDR of 31dB (Dawson et al. 2007) and which compared an IIDR of 40dB to that of 30dB (Holden et al. 2007).

Sentences in quiet were reported in three studies. No change (Holden et al. 2007) or a small significant decrease in perception (Veekmans et al. 2010) were reported when comparing IIDR expansion from 30dB to 40dB and 30dB to 50dB respectively. Spahr et al. (2007) indicated a small significant improvement for IDRs of 50dB and 60dB when compared to an IDR of 30dB.

Sentences in noise were reported in seven studies. James et al. (2003) indicated a medium significant decrement in speech-in-noise perception using BKB sentences presented at 65dB SPL in eight talker-babble with a SNR chosen to produce a keyword correct score of greater than 35%, but less than 70% when expanding IIDR from 30dB to 38dB. Three studies indicated no significant change to perception; Davidson et al. (2009) for sentences presented at 65dB SPL using four talker-babble with SNR at SRT when expanding IIDR from 30 to 40dB; Dawson et al. (2007) for sentences presented at 65dB SPL using eight talker-babble with subject specific SNR when expanding IIDR from 30 to 40dB and Holden et al. (2011) for sentences presented at 65dB SPL using eight talker-babble with subject specific SNR when expanding IDR from 50 to 65 to 80dB.

Three studies reported a small, but significant improvement to perception. Veekmans et al. (2010) for sentences presented at 60dBA with noise at +5dB SNR, when expanding IIDR from 30 to 50dB; Holden et al. (2007) for sentences 65dBSPL in eight talker-babble at user specific SNR when expanding IIDR from 30 to 40dB and Spahr et al. (2007) using speech presented at 77dBSPL at +10dB SNR for IDR wider than 30dB.

Stimulation rate adjustment:

The range of stimulation rates tested across the seventeen studies was from 250pps/e to 5158pps/e.

There were eight studies exclusively reporting changes in stimulation rate for the Cochlear Ltd device, three which used the Advanced Bionics device, four which used the Med-El device, one which used the Neurelec device and one which used both the Cochlear Ltd and Advanced Bionics devices. Data is plotted in Figure 4 (monosyllabic word tests), Figure 5 (sentences in quiet) and Figure 6 (sentences in noise). Rates which provided a statistically significant increase in speech perception compared to at least some of the other rates tested

are highlighted in grey. Instances in which a higher rate produced a statistically significant decrease in speech perception are highlighted in black. Studies which showed no significant effect of change in rate have not been plotted but these are included in Table 4.

Figure 4

Figure 5

Figure 6

Figure 4 shows significant change to monosyllable perception and rate change for five studies, of which two used the Med-El device, one the Advanced Bionics, one the Cochlear Ltd and one the Neurelec device. Differences exist for the mode of monosyllabic word presentation, test level used and test material language for the reviewed studies, as described in Table 3. Park et al. (2012) used recorded monosyllabic material presented at 45dBHL, Loizou et al. (2000) used a direct input signal to a research processor at each subject's comfortable listening level and Buechner et al. (2010) gave no detail for the mode or intensity level for presentation.

Four from five studies reported improved monosyllabic word perception with increased rate, although this improvement did not continue for all higher rates examined. However, a decrement in monosyllabic word perception was reported by Park et al. (2012). Specific characteristics, which may have influenced the degraded response include the low monosyllable presentation intensity selected of 45dBHL, the single large step in rate change of 2.7 times the lower standard rate or the method of signal processing used within the Cochlear Ltd device.

Figure 5 plots sentence in quiet perception and rate change for two studies using the Advanced Bionics and Neurelec devices. CID sentences were presented at 70dB SPL in 'live voice' (Di Lella et al. 2010). HSM sentences were used, but no detail for the mode or intensity level for presentation was provided for (Buechner et al. 2010). Both studies report a moderate significant improvement in sentence perception for a higher stimulation rate, but the interpretation of this outcome is limited by study design and an absence of experimental detail.

Figure 6. plots sentence in noise perception and rate change for six studies of which four used the Cochlear Ltd device, one the Advanced Bionic and one Neurelec. Limited consistency existed for the mode and presentation level of sentences in noise. (Arora et al. 2011; Battmer et al. 2010) used a stimulus level of 65dBSPL, calculating an SRT_{50} , that is a SNR ratio when 50% of the sentences are correctly perceived. However, these studies differed by sentence material, language and noise type. Di Lella et al. (2010) and Vandali et al. (2000) used a stimulus intensity of 70dBSPL at either a single fixed SNR of +10dB or at three fixed steps between 0 and +20dB SNR, which were described as low, medium and high SNR levels. However, these differed by sentence material, language and mode of presentation; live voice versus recorded.

Holden et al. (2002) tested at three intensities of 50,60 and 70dBSPL using subject specific fixed SNR, which provide a correct perception score of between 30% and 75%. No detail for the mode or presentation intensity level was provided for Buechner et al. (2010), although confirmation of a +10dB SNR was given.

Four from six studies reported improved sentence in noise perception with increased rate, although this improvement did not continue for all higher rates examined. A decrement in sentence in noise perception was reported in two studies, Battmer et al. (2010) reported a small significant decrement in speech in noise perception for a rate of 3500pps/e when

compared to 500pps/e and 1200pps/e and Vandali et al. (2000) reported a medium and large significant decrement in speech in noise perception for 1615pps/e when compared to 807pps/e and 250pps/e for the middle and lowest SNR tested.

Battmer et al. (2010) reported a potential confounding factor in his study, which was the presence of stimulation rate bias; some study subjects had used a 1200pps/e stimulation rate for 13-33 weeks prior to enrolment.

Vandali et al. (2000) indicated a large significant interaction between subject and rate, for the middle and lowest SNR tested, indicating the speech-in-noise perception scores varied from subject to subject with rate of stimulation. Consequently, the authors further evaluated the influence of individual subject variance and reported that the significantly lower group mean scores obtained with the 1615pps/e compared with those of the two lower stimulation rates evaluated could be accounted for predominantly by the results of a single subject.

Complications:

The adjustment of T level, IDR and stimulation rate provided a reported complication in three studies. Holden et al. (2011) used the Advanced Bionics device and increased T level by raising this above perceptual hearing threshold to a level which provided a loudness rating of barely audible and very soft; they then compared three IDR levels of 50, 65 and 80dB. They reported that four subjects experienced a static-like noise in quiet with raised T levels and an increased IDR. Further exploration defined this to be system noise, which could be traced to the input microphone. Holden et al. (2002) and Vandali et al. (2000) evaluated change to rate of electrical stimulation in the Cochlear Ltd N24 device. Both authors reported subjects who experienced severe tinnitus when using a map with a higher rate of stimulation and in each case, the participants withdrew from the study.

Discussion:

Is speech perception improved by increasing T level?

Increasing T levels when programming a CI has the effect of improving the audibility of soft intensity sound by increasing corresponding electrical current stimulation.

From the reviewed papers, only Skinner et al. (1999) compared setting T level at a perceptual audible threshold with T levels raised to perceptual level which provides a loudness rating of very soft or medium using a speech perception outcome. For users of the Cochlear Ltd N22 system utilising presentation intensities of 50, 60 and 70dB SPL for both CNC monosyllables and CUNY sentences, they reported a medium significant improvement for monosyllable perception at 50 and 60dB SPL, but no change for 70dB SPL and a large significant improvement for sentences presented at 50dB SPL and a small significant improvement at 70dB SPL.

A significant change in sentence perception in noise following an increase to T level was reported only for Cochlear Ltd N24 users (Zhou and Pfungst 2014). Modulation detection thresholds (MDT) at 50% of the EDR were used to define five channels with the poorest averaged modulation sensitivity. Channels with poor MDT had an applied increase to T level of either 5 or 10% of the DR. SRTs were measured using the original T level map, where T was set to a perceptual hearing threshold; a T level plus 5% DR map and T level plus 10% DR map. A small significant improvement in SRT₅₀ for the T level plus 5% DR map was reported, which supports a more precise adjustment of individual channel parameters to improve recognition of speech in noise.

Increasing T levels in the Cochlear Ltd device either above perceptual behavioural level or as a proportion of the EDR has been reported to provide benefit to monosyllable perception for presentation at 50dB and 60dB SPL and for sentences in quiet at 50dB SPL.

Increasing T levels of specific electrodes with a poor MDT in the Cochlear Ltd N24 device provided an improved SRT for sentences presented at 60dBA in modulated noise.

For the Med-El, Advanced Bionics and Neurelec device, no studies examined the influence on speech perception ability using a method to effectively increase the setting of T level.

Is speech perception improved by increasing IDR?

The dynamic range of speech and the implication for optimal conversion to an auditory electrical stimulation pattern in CI has been investigated (Zeng et al. 2002). They evaluated the acoustic dynamic range of consonants and vowels with both acoustic broadband and narrowband analyses which provided an approximate distribution of speech envelope levels of 50dB. They then evaluated IDR change in steps of 10dB from 10dB to 80dB for Advanced Bionics CI users using vowels and consonants in quiet and in noise; this indicated speech perception to be optimal at a 50-60dB IDR. Despite a large variability in phoneme perception in noise, the use of a slightly narrower IDR provided improved recognition which derived from consonant recognition. Except for Veekmans et al. (2010) for the Cochlear Ltd device, perception of either monosyllables or sentences in quiet, remain unchanged or improve with a wider IIDR greater than 30dB. Speech in noise is reported to benefit from a narrower IIDR (James et al. 2003), but this contrasts with Davidson et al. (2009) and Dawson et al. (2007) who indicate no change and Veekmans et al. (2010) and Holden et al. (2007) who report a small significant improvement with a wider IIDR of 40dB. It must be considered that a significant interaction with the sensitivity parameter occurs in the Cochlear Ltd device, which cannot be viewed in isolation when examining the effect of IIDR.

The effect of IDR/IIDR expansion varied for the studies reviewed. The lack of consistency is influenced by several factors which include, the different methodology

employed by each manufacturer when translating an IDR into to an EDR, the wide variety of speech perception test materials used in studies, the reported between subject variability and the differing periods of adaptation afforded to subjects prior to measurement of speech perception.

In the Cochlear Ltd device, monosyllable and consonant recognition for soft intensity speech presented between 45dB SPL and 55dB SPL improved with an IDR increase to either 40dB or 46dB. An IDR of 40dB is the current default within the latest Cochlear Ltd fitting software (Custom Sound® v5.0).

In the Advanced Bionics device, a range of IDR between 65 to 80dB can be used to optimally perceive monosyllables in quiet, however any expansion above 65dB should be evaluated for an audible noise floor and consequently should be offered to CI users in the clinical setting who are able to provide feedback. For speech in noise an IDR of 50dB provided optimal outcomes. An IDR of 60dB is the current default within the latest Advanced Bionics fitting software (SoundWave™ v3.1).

Is speech perception improved by increasing stimulation rate?

Default stimulation rates offered by current CI devices at initial activation, assuming all electrodes are useable following a full intra-cochlear insertion, range from 1040pps/e for the Oticon Medical device (formerly the Neurelec system) to approximately 2700pps/e, which can be commonly found in the Advanced Bionics and Med-El devices.

Studies that evaluated rate of stimulation explored a range of stimulation rates which due to the use of older CI devices led to a more frequent exploration of slower stimulation rates than those offered as default in current CI devices. Due to differences in CI manufacturer system design, CI systems provide individual and contrasting range of stimulation rates. Speech perception outcomes were therefore reviewed by individual CI

manufacturer and stimulation rate. However, no clear effect upon speech perception when using an increased electrical stimulation rate by manufacturer could be established.

For electrical stimulation rate, no clear guidance can be defined as different rates will often provide a significant across subject variation in speech perception outcome, which in some cases can be so large as to cause a deviation from group mean trends (Keifer et al. 2000). An optimal stimulation rate is therefore likely to be specific to each subject.

Limitation of Systematic review:

The quality of studies included within the review was moderate to poor. As no randomised trials exist within the review, selection bias must be assumed to be a confounding factor in the outcomes reported. The adaptation period provided from parameter change to speech perception testing ranged from 5 minutes to 24 weeks with a median period of 3.5 hours.

When evaluating the effect of a parameter change with a sentence perception task in quiet or in fixed or adaptive noise, any increase to available speech perception cues may require a period of adaptation (Svirsky et al. 2015). Consolidation of new or changed speech cues to the perception of sentences over time can be protracted and vary across subjects, which is unlikely to be conducive to measuring change in an acute or chronic test design. The heterogeneity of subject selection, study design, test materials and languages limit the utility of the review to inform clinical practice or make recommendation.

Significant heterogeneity existed within the reviewed studies, preventing meta-analysis. However, the complications observed and reported in two studies may assist to inform future studies of possible expected adverse events providing more complete and robust information to potential study participants at recruitment. The inclusion of all CI manufacturers may have added complexity to the review as manufacturers utilise differing

techniques in signal processing and may or may not offer a method to manipulate all parameters.

Conclusion:

Adjustment of T level, IDR and stimulation rate within heterogeneous groups has led to a high variability in outcomes. The limited consistency in experimental design across multiple languages using differing test materials and afforded adaptation and follow up, further complicates the utility of the review for quantifying trends or provide clinical recommendation. Despite these limitations, the following can be defined:

- (1) T levels above behavioural threshold or as proportion of EDR has been demonstrated to improve perception of monosyllables in quiet and sentences in both quiet and in noise.
- (2) the use of wider IIDR/ IDR setting can improve perception of monosyllables in quiet, particularly at softer presentation intensity. The use of wider IIDR/ IDR setting for sentences in quiet and in noise provide mixed outcomes, which would necessitate a systematic evaluation if applied clinically.
- (3) no recommendation could be determined for rate of stimulation as speech perception varied significantly across the stimulation rates examined.

Although manufacturer defaults for parameter settings, provide a useful first setting, they may not provide the most effective setting. This is acknowledged to contribute to the significant across subject variability for speech perception reported in the review.

Consequently, a prevailing recommendation is for bespoke parameter settings to be applied to individual subjects. Further research to provide recommendations for configuration of individual settings remains a challenge. However, to define an individualised configuration will ensure optimal device mapping and the most advantageous setting for speech perception

across a variety of intensities, in quiet and in competing noise.

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Table 1. Characteristics of threshold (T) level studies

Study	No. subjects	Age	Device	Design	Assessment	Duration of experience	OCEBM Level	Valente Level
Baudhuin et al. (2012)	11	7 – 17 years	Advanced Bionics Hi-Res90K or CII	Effects of two T-level settings - 10 cu below soft and 10% of M level	Ling 6 sounds and soundfield threshold detection to FM tones.	2 x 3 hour sessions	3	3BEFII
Boyd (2006)	17	41 – 70 years	Med-El Combi 40+	Three test maps were produced to examine how the Programming Threshold PT setting affected acoustic thresholds and speech discrimination.	Soundfield threshold detection to FM tones for 0.5, 1, 2 and 4kHz. BKB sentences at 65dBA – Test map 2 excluded.	2-3 minutes	4	3BEFII
Holden et al. (2011)	10	49 – 80 years	Advanced Bionics Hi-Res90K or CII	Effect of three T-level settings – 10% of M, barely audible and very soft. Chronic exposure, few weeks use	Soundfield threshold detection to FM tones CNC words at 50dBSPL and CUNY sentences at 65dBSPL with four talker babble using an individual subject SNR to obtain a score between 50 and 75% correct	1-2 weeks	3	3CEFII
Zhou et al. (2014)	7 subjects – 9 ears	28 – 72 years	Nucleus 24 CI24RE(CA) and CI24R(CS) CP810 and Freedom speech processor	To examine the effect of rehabilitating electrodes with poor Amplitude Modulation Detection Thresholds (MDT) by increasing minimum stimulation level at the poorly performing sites.	CUNY sentences in adaptive modulated background noise. SNR started at 20dB and was adapted in a one down one up procedure using a 2dB step size. SRT was taken for the mean SNR of the last 6 reversals.	Chronic, no experience	3	3CEFII
Spahr and Dorman (2005)	15	Adult subjects	Med-El Tempo+	Effect of three minimum stimulation level settings; behavioural T level, T level at 10% of M level or T level at 0 μ A.	Sentences in quiet at 54dB SPL in noise at 74dB SPL with +10dB SNR using 4-talker babble. Vowels presented in the b/v/t context at 54dB SPL vowel peak and Consonants in the e/C/e context at 74dB SPL vowel peak.	Chronic, no experience	2	3CEFII
Fu et al. (2000)	3	39 – 55 years	Nucleus 22	To determine phoneme recognition of errors in setting threshold and loudness levels in cochlear implant listeners using a 4-channel continuous interleaved sampling (CIS) speech processor. C level remained fixed and the T level was either elevated or reduced to give six dynamic range values of 1, 2, 3, 6, 12, and 20dB.	Vowel recognition was measured in a 12-alternative identification paradigm. Consonant recognition was measured in a 16-alternative identification paradigm. All material was presented at user comfort level.	No appreciable experience	4	4CEFII
Tanamati et al. (2005)	30	11 – 66 years	Med-El Combi 40+, 16 subjects using Tempo+ and 14 subjects using CIS-Pro	Comparison of speech perception for maps using psychophysical T level setting and T at 10% of C level.	Monosyllables in quiet at 70dB SPL and sentences in quiet and in noise at 70dB SPL with +10dB SNR	30 minutes	3	3CEFII
Skinner et al. (1999)	8	39 – 70 years	Nucleus 22	Comparison of two methods for setting T level; (i) Calculated mean thresholds for two sessions were applied and balance for loudness (ii) Threshold set between perceptually very soft and medium. A ₁ B ₁ A ₂ B ₂ test design.	Soundfield threshold detection to FM tones and loudness scaling judgement for four-talker babble. CNC monosyllables presented at 50, 60 and 70dB SPL. CUNY sentences in 8 talker babble presented at 50, 60 and 70dB SPL with a SNR chosen for each participant to prevent ceiling and floor effects.	2-3 weeks	3	3CEV&EFII

Table 2. Characteristics of IDR studies

Study	No. subjects	Age	Device	Design	Assessment	Duration of experience	OCEBM Level	Valente Level
Veekmans et.al.	150	1.4 –12.2 years	Nucleus 24M (86) and 24R (64)	Comparison of 30dB IIDR and 50dB IIDR – 3G to Freedom	Soundfield aided measurements at 0.5, 1, 2 and 4kHz; BKB sentences in quiet at 60 and 50BA and in noise at 60dBA +10 and +5dB SNR.	Acute	3	3CEFII
Holden et al.	10	49 – 80 years	Advanced Bionics Hi-Res90K or CII	Effect of three different IDR settings, 50dB, 65dB and 80dB	Soundfield threshold detection to FM tones CNC words at 50dBSPL and CUNY sentences at 65dBSPL with four talker babble using an individual subject SNR to obtain a score between 50 and 75% correct	1-2 weeks	3	3CEFII
Zeng et al.	10	21 – 56 years for Cochlear Implant users, 21 – 36 years for normal hearing controls.	Advanced Bionics C1 7 subjects using CIS and 3 subjects using SAS stimulation strategies. 5 normal hearing controls.	CIS users tested six settings of IDR from 10 to 60dB in 10dB steps and SAS users tested six settings from 20 to 80dB in 10dB steps	Phoneme recognition using vowel stimuli of 12 tokens and consonant stimuli of 20 tokens from five male and five female talkers presented at 65dBA and in speech shaped noise at +5dB SNR	15 minutes	3	3CEFII
Spahr et al.	76	Advanced Bionics CII HiRes with positioner – 55 years; Cochlear CI24M or RCS – 50.5 years MedEL Combi 40+ - 52.2 years	Advanced Bionics CII HiRes with positioner - 26 subjects; Cochlear CI24M or RCS - 32 subjects; MedEL Combi 40+ - 18 subjects.	Experiment 3 – To assess the effects of increasing IDR in the CII device.	Experiment 3 - Effect of increasing input dynamic range in the CII device was assessed with sentence material presented at conversational levels in quiet at 77dBSPL, conversational levels in noise at 77dBSPL +10SNR, and soft levels in quiet at 57dBSPL	5 minutes	3	3CEFII
Davidson et al.	30	7-17 years	Nucleus 24 with Freedom Speech Processor	Comparison of two different Instantaneous IDR (IIDR) of 30 and 40dB	CNC wordlist at 50, and 60dBSPL, BKB sentences in noise, a loudness rating task for four talker speech noise, soundfield aided thresholds to narrow band noise and a calculated speech intelligibility index (SII).	4 weeks	2	3CEV&EFII
Holden et al.	10	36 – 80 years	Nucleus Freedom Cochlear Implant	Comparison of two maps with different IIDR, the first with an IIDR of 30dB and the second an IIDR of 40dB. Both maps use the ACE strategy (25 µs/phase, monopolar stimulation), 1200 pulses per second /channel (pps/ch) stimulation rate and 10 maxima. Controlled for order bias; chronic exposure.	Soundfield threshold detection to FM tones. CNC monosyllables at 50dB SPL, HINT sentences at 50dB SPL and CUNY sentences in 8 talker- babble noise at 65dB SPL with an SNR chosen for each participant to prevent ceiling and floor effects	4 weeks	3	3CEFII
Dawson et al.	9	50 – 77 years	Nucleus CI22 and CI24 Cochlear Implants	Repeated measures, single subject design with chronic exposure and counterbalanced order comparing IIDR of 31 dB, reduced T 46dB, 46 dB, reduced T 56dB and 56 dB.	CNC monosyllables presented at 45 and 55 dB SPL (RMS). CUNY sentences resented at 65dB SPL in 8 talker-babble noise with an SNR chosen for each participant to prevent ceiling and floor effects	4 weeks	3	3CEV&EFII
James et al.	12	59 – 83 years	Nucleus 24	Part 2 – of the experimental design varied instantaneous input dynamic (IIDR)	Soundfield threshold detection to FM tones Consonants in the a/C/a context; vowels in the h/V/d context at 40 and 55dB SPL. BKB sentences at 65dB SPL with 8 talker babble with an SNR chosen for each participant to prevent ceiling and floor effects	2-3 weeks	3	3CEV&EFII

Table 3.Characteristics of stimulation rate studies

Study	No. subjects	Age	Device	Design	Assessment	Duration of experience	OCEBM Level	Valente Level
Arora et al.	10 with inclusion of speech test results from 8 subjects from an earlier study in 2009	58 – 74 years	Cochlear Nucleus CI24	Effect of low to moderate stimulation rates (275, 350, 500 and 900pps/ch) on modulation detection threshold (MDT) ability. The relationship between MDT and speech perception as a function of rate was examined.	Four lists CNC monosyllabic words in quiet at 60dB SPL RMS and an adaptive SRT using speech intelligibility test (SIT) sentences at 65dB SPL using four talker babble proving an SNR	24 hours	3	3CEV&EFII
Balkany et al.	71	23 – 90 years	Cochlear Nucleus Freedom	Multi-centre randomised, controlled, prospective, single-blinded, single subject repeat measures design.	Soundfield threshold detection 0.25 to 8kHz for FM tones HINT sentences in quiet at 60dB SPL, CNC words/ phonemes in quiet at 60 and 70dB SPL. HINT sentences in noise at 60dB SPL SNR 10dB and CUNY sentences in noise at 70dB SPL SNR 10dB	2-4 weeks	2	3CEV&EFII
Battmer et al.	Group 1 – 29 subjects Group 2 – 19 subjects Group 3 – 20 subjects	24 – 72 years 19 – 77 years 24 – 80 years	Cochlear Nucleus CI24RE	Group 1 – Comparison of the effects of different pulse rates on speech perception performance (subjects had prior experience with 1200pps) Group 2 – Preferred pulse rate post activation (no within-subject comparison for the effect of pulse rate) Group 3 – Randomised, single blinded, subjects offered two pulse rates at activation	Freiburg words at 60 and 70dB SPL, Oldenburg sentences in quiet at 65dB SPL and in noise at 65dB SPL scored as an SNR at 50% correct or SNR Disyllabic word test in quiet and at a fixed SNR	5-33 weeks	3	3CEV&EFII
Bonnet et al.	27	17 – 77 years	Advanced Bionics CII and Hi-Res90K	To assess 9 different 12 channel strategies using monopolar mode, biphasic pulses and no interphase gap. An interpulse interval was used to maintain rate where pulse width was manipulated.	Dutch monosyllabic consonant-vowel-consonant word test in quiet at 65dB SPL and in noise at +10 and +5dB SNR using speech shaped noise.	1 hour	3	3CEFII
Buechner et al.	13	17.7-73.0 years	Advanced Bionics CII with Hi-Focus electrode array and electrode positioned system	A prospective repeated-measure in a chronic balanced cross-over design evaluating the influence upon speech perception of different stimulation rates and the use of sequential or paired stimulation patterns.	Freiburger monosyllable word test in quiet, HSM sentence test in quiet and in noise with 10dB SNR	4 weeks	3	3CEV&EFII
Di Lella et al.	10	28 – 66 years	Neurelec-MXM	Prospective within subject repeated measures design to evaluate the speech recognition performance using the MPIS strategy at two stimulation rates	NU 6 word list and CID sentences presented live at 70dB SPL voice in quiet and in talker babble noise at +10dB SNR	6 weeks	3	3CEV&EFII
Friesen et al.	Advanced Bionics CI, N=5; Cochlear Nucleus 24, N=4; Advanced Bionics CII, N=3	38 – 66 years	Advanced Bionics CI, Cochlear Nucleus 24 and Advanced Bionics CII	To investigate speech perception following adjustment of rate and stimulus channel number.	Vowels in h/V/d context Consonants in a/C/a context. CNC wordlist, HINT sentences and IEEE sentences. Materials presented at 65dB SPL for CI and N24; 70dB SPL for CII.	Chronic, no experience	3	3CEFII
Holden et al.	8	36 – 81 years	Cochlear Nucleus CI24M	To evaluate speech recognition with the ACE strategy at two stimulation rates 720 pps/ch and 1800pps/ch and to determine if the group or individuals performed better or demonstrated a preference following chronic exposure	Soundfield threshold detection 0.25 to 6kHz for FM tones CNC monosyllables and CUNY sentences presented in at 50, 60 and 70dB SPL with 8 talker babble noise. Preference questionnaire.	3-4 weeks	3	3CEV&EFII

Table 3. (continued)

Kiefer et al.	13	Not described	Med-El Combi 40 N=9 Med-El Combi 40+ N=4	To systematically evaluate the reduction of stimulation rate from 1515 and 1730 ppse to 600ppse and channel number from 8 to 4.	Eight German vowels in b/V/b context and sixteen consonants in a/C/a context at 65dBHL. Freiburg monosyllabic words and 2-digit	10 minutes	3	3CEFII
Loizou et al.	6	40 – 68 years	Med-El Link experimental device	To systematically evaluate the effect of stimulation rate on speech perception.	CNC monosyllabic words, 20 consonants in v/C/v context and vowels in h/V/d context. Presented at a 'comfortable' listening level.	Chronic, no experience	3	3CEFII
Nie et al.	5	24 – 57 years	Med-El Combi 40+	Experiment 2. To evaluate the variation of stimulation rate from 1000 to 4000Hz per electrode on four fixed pairs of electrodes	12 vowels in h/V/d context and 20 consonants in a/C/a context. HINT sentences male speaker in quiet and in noise at 10dB SNR, presented at user comfortable listening level.	10 minutes	3	3CEFII
Park et al.	6	17 – 43 years	Nucleus 24 contour	To investigate speech recognition performance of CI users in quiet and in noise for moderate and high stimulation rates – 900ppse and 2400ppse. Prospective, cross-over study design, chronic exposure.	Monosyllabic wordlist, presented at 45dBHL. Sentence test in white noise presented at 50dBHL with 15dB SNR initially adapted to maintain a target correct of 70%. Preference questionnaire.	2 weeks	3	3CEV&EFII
Plant et al.	15	26.9 - 75.2 years	Cochlear Nucleus Ci24RE with contour electrode	A repeat measures single subject design using an ABAB protocol. Program A used a stimulation rate between 12kHz and 14.4kHz and program B used a stimulation rate of either 24kHz or 32kHz dependent upon subject preference.	CNC monosyllables in quiet at 60dB SPL RMS and CUNY sentences in quiet at 65dB SPL RMS and in noise using 8 talker babble with an SNR between +5dB and +14dB adjusted for individuals to prevent floor and ceiling effects.	2-24 weeks	3	3CEV&EFII
Plant et al.	12	32 – 76 years	Cochlear Nucleus Ci24M	Assess the effect of parameter adjustments in the ACE and CIS strategies. Study II. Evaluation of CIS stimulation rates of 275, 900, 1800 and 2400Hz for a fixed six channel program. Balanced order across sessions and subjects to limit order and learning effects.	CNC monosyllables in quiet at 65dBA and CUNY sentences presented at 65dBA in eight-talker babble noise at a SNR specific to each test subject to limit floor and ceiling effects	Chronic, no experience	3	3CEFII
Shannon et al.	7	33 – 59 years	Advanced Bionics CII with Hi-Focus electrode array and electrode positioned system	Evaluate the effect of stimulation rate and channel number on speech perception. Pulse rate varied between 600 and 4800ppse in an acute experimental design.	Medial Vowel in the h/V/d context and Medial Consonant recognition in the a/C/a context, CNC words and IEEE sentences presented in quiet at 70dBA and in speech shaped noise at +10dB SNR	Acute	4	3CEFII
Vandali et al.	6 recruited, 5 data sets reported	44 – 70 years	Cochlear Nucleus Ci24M, SPEAK speech processing strategy and SPRINT speech	To investigate the effect of varying electrical stimulation rate on speech comprehension. A repeated ABC design with alternating order with chronic exposure to each stimulation rate.	CNC monosyllables in quiet and CUNY sentences in multi-talker noise at three SNRs which were subject dependent to limit floor and ceiling effects	4 weeks	3	3CEFII
Verschuur	6	29 – 73 years	Med-El Combi 40+ and Ineraid Cochlear Implant systems	Determine the effect of altering channel stimulation rate. Three stimulation rates assessed, the subjects clinical rate, 400pps/ch and 800pps/ch. Order of rate condition and test within each rate condition was counterbalanced in an experimental acute design	Categorical perception of synthetic speech stimuli with varied acoustic cues; consonant recognition measure (VCV) in the i/C/i context and BKB sentences administered in quiet at 70dBA	30 minutes	3	3CEFII

Table 4. Summary

Variable	Paper	Device	Monosyllable words	Monosyllable test level	Phonemes	Vowels	Consonants	Sentences in quiet	Sentence in quiet test level	Sentence in noise test level	Sentences in noise	Noise type - SNR	Outcome in quiet	Outcome in noise
Effect of T level increase or decreasing electrical dynamic range														
T Level	Baudhuin 2012	ABionics CII HiRes90K						BKB	65dBA				=	
	Boyd 2006	Med-El Combi40+				+	+							
	Fu 2000	Cochlear N22												
	Holden 2011	ABionics CII HiRes90K												
	Skinner 1999	Cochlear N22	++	50, 60 and 70dBSPL	++			CUNY	50, 60 and 70dBSPL				+++	
	Spahr 2005	Med-El Tempo+				=	=	CONVERSATIONAL SENTENCE STYLE	54dBSPL	74dBSPL	CONVERSATIONAL SENTENCE STYLE	74 dBSPL at +10 dBSNR, 4-talker babble	=	=
	Tanamati 2005	Med-El Combi40+	=	70dBSPL				PORTUGUESE SENTENCES	70dBSPL	70dBSPL	PORTUGUESE SENTENCES	70dB SPL at +10dB SNR, noise type not specified	=	=
	Zhou 2014	Cochlear N24, CP810 and Freedom SP								60dBA	CUNY	Adaptive modulated white noise with SNR at SRT - 50% correct calculated		+
Effect of IDR or IIDR increase														
IDR	Holden 2011	ABionics CII HiRes90K	++	50dBSPL						65dBSPL	CUNY	SNR limiting floor and ceiling +5 to +14dB		=
	Veekmans 2010	Cochlear N24						BKB	50, 60dBA	60dBA	BKB	Noise type not specified, SNR +10dB and +5dB	-	+
	Davidson 2009	Cochlear N24, Freedom SP	+++	50, 60 dBSPL						65dBSPL	BKB-SIN	Four talker babble with SNR at SRT - 50% correct calculated		=
	Holden 2007	Cochlear N24	+++	50dBSPL	+++	=	+++	HINT	50dBSPL	65dBSPL	CUNY	Eight talker babble, SNR limiting floor and ceiling +10dB to +20dB	=	+
	Spahr 2007	ABionics CII HiRes90K, Cochlear N24, Med-El Combi40+						CUNY	57, 77 dBSPL	77dBSPL	AZ-BIO	Four talker babble - +10dB SNR	+	+
	Dawson	Cochlear N22 and N24	+++	45, 55 dBSPL		+++	+++			65dBSPL	CUNY	Eight talker babble, SNR to limiting floor and ceiling		=
	James 2003	Cochlear N24				=	++			65dBSPL	BKB	Eight talker babble, SNR to limiting floor and ceiling		- -
	Zeng 2002	ABionics C1				++	++					Speech spectrum shaped noise, SNR +5dB		
Effect of stimulation rate increase														
Rate	Arora 2011	Cochlear N24	=	60dBSPL						65dBSPL	SIT	Four talker babble with SNR at SRT - 50% correct calculated		+++
	Balkany 2007	Cochlear N24	=	60, 70dBSPL				HINT-Q	60dBSPL	60, 70dBSPL	HINT/ CUNY	Noise type not specified, SNR +10dB	=	=
	Battmer 2010	Cochlear N24	=	60, 70dBSPL					65dBSPL	65dBSPL	OLDENBURG	Noise type not specified, SNR at SRT - 50% correct calculated		-
	Bonnet 2012	ABionics CII HiRes90K	=	65dBSPL								Speech shaped noise, SNR +5dB and +10dB		
	Buechner 2010	ABionics CII	++	Not specified				HSM			HSM	Noise type and presentation intensity not specified, SNR +10dB	++	++
	Di Lella 2010	Neurelec MXM	++	70dBSPL				CID		70dBSPL	CID	Talker babble, +10dB SNR	++	++
	Friesen 2005	ABionics C1, Cochlear N24, ABionics CII	=	65, 70dBSPL		=	=	HINT/ IEEE		65, 70dBSPL			=	
	Holden 2002	Cochlear N24			+			CUNY		50, 60 and 70dBSPL	CUNY	Eight talker babble, SNR limiting floor and ceiling		+++
	Kiefer 2000	Med-El Combi40+	++	75dBHL			+							
	Loizou 2000	Med-El Link device	+	Comfortable loudness		=	+++							
	Nie 2006	Med-El Combi40+		Comfortable loudness		=	+	HINT		Comfortable loudness	HINT	Single female talker at 10dB SNR		
	Park 2007	Cochlear N24	-	45dBHL						50dBHL	KOREAN STANDARD SENTENCES	White noise, adaptive SNR		=
	Plant 2007	Cochlear N24	=	60dBSPL						65dBSPL	CUNY	Multi-talker babble, SNR limiting floor and ceiling		=
	Plant 2002	Cochlear N24	=	65dBA						65dBA	CUNY	Eight talker babble, SNR limiting floor and ceiling		=
	Shannon 2011	ABionics CII	=	70dBA		++	=	IEEE	70dBA	70dBA	IEEE	Speech spectrum shaped noise, SNR +10dB	=	=
	Vandali 2000	Cochlear N24	=	70dBSPL		- -	=			70dBSPL	CUNY	Multi-talker babble, three SNRs - low, middle and high		- - - / - -
	Verschuur 2005	Med-El Combi40+, Ineraid					=	BKB		70dBA			=	

+++ Indicates a significant positive outcome ($p < 0.001$), ++ Indicates a significant positive outcome ($p < 0.01$), + Indicates a significant positive outcome ($p < 0.05$), = Indicates no significant difference, - Indicates a significant negative outcome ($p < 0.05$), - - Indicates a significant negative outcome ($p < 0.01$), - - - Indicates a significant negative outcome ($p < 0.001$). Where multiple test intensities exist, the test intensity which provided a result of statistical significance is in 'bold' font. Where multiple device manufacturers exist within the same study, the manufacturer which provided a result of statistical significance is in 'bold' font

FIG. 1. MEDLINE/ EMBASE search strategy

Key

\$ = retrieve unlimited suffix variations

adj2 = searches for terms that are (2) spaces away from each other

FIG. 2. Flow chart of selection method

FIG. 3. Quality of studies

FIG. 4.

Stimulation rates within each study providing a significant improvement in speech perception score are in grey; rates providing a significant decrease in speech perception score, which coincide with a higher stimulation rate are in black.

FIG.5.

Plot of stimulation rate change evaluated by studies using sentence perception in quiet as an outcome. Rates providing a significant improvement in perception in quiet are in grey.

FIG.6.

Plot of stimulation rate change evaluated by studies using sentence in noise perception as an outcome. Rates providing a significantly improved perception score are in grey; rates providing a significant decrease, which coincide with a higher stimulation rate are in black.