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Groesen, N.R.A. van; Briaire, J.J.; Jong, M.A.M. de; Frijns, J.H.M.

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Dynamic Current Focusing Compared to Monopolar Stimulation in a Take-Home Trial of Cochlear Implant Users

Nicolaas Roelof Arnoldus van Groesen,¹ Jeroen Johannes Briaire,¹
Monique Anna Maria de Jong,¹ and Johannes Hubertus Maria Frijns^{1,2}

Objectives: This study compared the performance of a dynamic partial tripolar cochlear implant speech encoding strategy termed dynamic current focusing (DCF) to monopolar stimulation (MP) using spectro-temporal, temporal, and speech-in-noise recognition testing.

Design: DCF is a strategy that utilizes tripolar or high partial tripolar stimulation at threshold level and increases loudness by slowly widening current spread towards most comfortable level. Thirteen cochlear implant users were fitted with DCF and a non-steered MP matched on pulse rate, pulse width, and active electrodes. Nine participants completed the single-blinded within-subject crossover trial. Repeated testing consisted of four sessions. Strategies were allocated in a DCF-MP-DCF-MP or MP-DCF-MP-DCF design. Three-week adaptation periods ended with a test session in which speech-in-noise recognition (matrix speech-in-noise sentence test), spectro-temporal ripple tests (SMRT and STRIPES) and a temporal amplitude modulation detection test were conducted. All participants recorded their subjective experiences with both strategies using the Speech, Spatial and Qualities of Hearing Scale questionnaire.

Results: Participants' SMRT thresholds improved 0.40 ripples per octave ($p = 0.02$, Bonferroni-corrected: $p = 0.1$) with DCF over MP at 65 dB SPL. No significant differences between the strategies were found on speech-in-noise recognition at conversational (65 dB SPL) and soft (45 dB SPL) loudness levels, temporal testing, STRIPES, or the SMRT at 45 dB SPL. After Bonferroni correction, a learning effect remained on the matrix speech-in-noise sentence test at both loudness levels (65 dB SPL: $p = 0.01$; 45 dB SPL: $p = 0.02$). There was no difference in learning effects over time between DCF and MP. Similarly, no significant differences were found in subjective experience on the Speech, Spatial and Qualities of Hearing Scale questionnaire. DCF reduced average battery life by 48% (5.1 hours) ($p < 0.001$) compared to MP.

Conclusions: DCF may improve spectral resolution over MP at comfortable loudness (65 dB SPL) in cochlear implant users. However, the evidence collected in this study was weak and the significant result disappeared after Bonferroni correction. Also, not all spectral tests revealed this improvement. As expected, battery life was reduced for DCF. Although the current study is limited by its small sample size, considering previous studies, DCF does not consistently improve speech recognition in noise over MP strategies.

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Key words: Cochlear implant, Current focusing, Speech perception testing.

Abbreviations: aMDT = Amplitude modulation detection test; dB SPL = Decibel sound pressure level; DCF = Dynamic current focusing; K = An

¹Otorhinolaryngology and Head and Neck Surgery, Leiden University Medical Center, Leiden, the Netherlands; and ²Leiden Institute for Brain and Cognition, Leiden, the Netherlands.

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interaction coefficient that incorporates the contribution from the electrical fields generated by the side electrodes to the peak of the electrical activation function in partial tripolar stimulation; LMM = Linear mixed-effects model; MCL = Most comfortable level; MP = Monopolar stimulation; MST = Matrix speech-in-noise sentence test; RPO = Ripples per octave; SMRT = Spectral-temporally modulated ripple test; SNR = Signal-to-noise ratio; SRT = Speech reception threshold; SSQ = Speech, spatial and qualities of hearing scale questionnaire; STRIPES = Spectral-temporal ripple for investigating processor effectiveness; THL = Threshold level; σ = Fraction of current absorbed by flanking electrodes in partial tripolar stimulation.

INTRODUCTION

For many years, cochlear implant research has made an effort to narrow the electrical field of speech encoding strategies through multipolar stimulation of the cochlea, also known as current focusing. As a proposed solution to poor spectral discriminatory abilities and a way to improve speech recognition in quiet as well as in noise, current focusing can lead to narrower excitation patterns (van den Honert & Stypulkowski 1987; Kral et al. 1998; Bonham & Litvak 2008; Landsberger et al. 2012; Kalkman et al. 2014; Wu & Luo 2016) and improved spectral resolution (Berenstein et al. 2008; Landsberger et al. 2012; Smith et al. 2013); the ability to discriminate percepts in the frequency domain. As spectral discrimination correlates with speech recognition (Henry & Turner 2003; Won et al. 2007; Henry et al. 2005; Holden et al. 2016; Lawler et al. 2017; Luo et al. 2020), current focusing can potentially lead to improved speech recognition in noise compared to monopolar stimulation (MP) (Srinivasan et al. 2013; Arenberg et al. 2018). Not all studies have reported this improvement in speech recognition (Berenstein et al. 2008; Snel-Bongers et al. 2012; Vellinga et al. 2017; Luo et al. 2021). Of these focused configurations, tripolar stimulation and partial tripolar stimulation have been researched extensively. In tripolar stimulation, all current is returned to the flanking electrodes instead of to the extracochlear return electrode, creating a current loop within the cochlea that allows for steeper voltage gradients. In partial tripolar stimulation, a fraction of current (σ) is directed to the flanking electrodes, and the remaining fraction ($1 - \sigma$) is returned to the extracochlear return electrode. Tripolar stimulation requires significantly more current compared to conventional MP and partial tripolar stimulation (Bierer 2007; Vellinga et al. 2017), resulting in a reduced battery life and sometimes leading to incomplete loudness growth due to the voltage compliance limits of the device (Litvak et al. 2007; Bierer & Litvak 2016). In conventional MP stimulation, all current is stimulated from one electrode and returned to the extracochlear return electrode.

Partial tripolar stimulation achieves a reduction in current consumption compared to tripolar stimulation by allowing a fraction of the current to be returned to the extracochlear electrode (Bierer 2007). At least 50% of the current has to be directed to flanking electrodes to effectively narrow the electrical field over MP (Berenstein et al. 2008; Bonham & Litvak 2008; Landsberger et al. 2012). Both tripolar and partial tripolar configurations still rely on the addition of current to induce loudness growth, which widens the electrical field at higher loudness levels (Chatterjee & Shannon 1998; Kalkman et al. 2016) and could inhibit the earlier mentioned possible gain of a narrower current spread with focused stimulation.

To counter this issue, de Jong et al. (2019a) developed a strategy termed dynamic current focusing (DCF). This strategy comprises a tripolar or highly focused partial tripolar configuration at threshold level (THL) and gradually increases perceived loudness by broadening the electrical field. Loudness is generated by increasing the spread of excitation and decreasing the fraction of current focusing. The broadened electrical field stimulates increasing numbers of spiral ganglion cells, thereby increasing the perceived loudness. No additional current is added in this process.

To the best of our knowledge, only Arenberg et al. (2018) and Nogueira et al. (2017) have investigated similar dynamic focusing configurations, although Nogueira's work involved virtual channels and added current steering through quadrupolar stimulation instead of physical electrodes. Because Nogueira et al. combined focusing with steering and did not conduct speech or spectro-temporal testing, we cannot directly compare the performance of their strategy to the dynamic strategies of Arenberg (2018) and de Jong (2019a, 2019b).

Arenberg (2018) compared a 14-channel dynamic focusing strategy to a newly fitted 14-channel MP and a partial tripolar strategy (σ : 0.8) in 20 postlingually deafened subjects. Programs were matched for pulse duration, filter settings and loudness on a channel-by-channel basis and tested in the acute setting. Speech recognition testing consisted of closed set spondees in noise and vowels in quiet and in noise, all at 50 and 60 dB SPL through a direct audio input cable. The study found a small but significant improvement in vowel recognition in noise for dynamic focusing over MP and the partial tripolar strategy. This improvement was not found for recognition of vowels in quiet or spondees in noise.

De Jong's pilot study (2019a) acutely compared DCF with a subject's unmatched clinical strategy (HiRes-S-F120 or HiRes Optima) in 11 unilaterally implanted subjects. DCF consisted of 14 channels while the clinical strategy consisted of 16 channels. The mean pulse rate was 2550 pps for the clinical strategies (Advanced Bionics Optima-S, HiRes-S-F120) and 817 pps for DCF. Testing consisted of a closed set matrix speech-in-noise sentence test (MST) (Hagerman 1982; Luts et al. 2014), the spectro-temporally modulated ripple test (SMRT) (Aronoff & Landsberger 2013) at 65 and 45 dB SPL, as well as an adaptation of Won et al.'s temporal amplitude modulation detection test (aMDT) (Bacon & Viemeister 1985; Won et al. 2011) to measure amplitude modulation detection thresholds at 65 dB SPL. Testing was conducted in the free field. As these tests are identical in setup to the ones used in the current study, more details are presented in the Materials and Methods. DCF was found to significantly improve performance on the SMRT at 45 dB SPL. No significant differences were found for speech-in-noise recognition, spectro-temporal ripple discrimination at conversational loudness, or on the temporally oriented aMDT.

Because dynamic focusing strategies apply more focus at THL, de Jong's pilot study (2019a) outcomes of improved speech-in-noise recognition and spectral ripple testing at lower loudness levels can be considered proof of principle. As a follow-up to the promising pilot study, de Jong completed a take-home trial (2019b) comparing DCF with 5 weeks of adaptation at home to the subjects' clinical strategy at baseline and 5 weeks after the DCF test session as a control for possible learning effects. Psychophysical testing was identical to the pilot study. Seventeen subjects completed the trial. This time, DCF significantly improved spectral ripple performance at 65 dB SPL compared to baseline, but no differences were found compared to the control session 5 weeks later. DCF failed to improve on the speech-in-noise recognition testing at 45 dB SPL compared to baseline and control, whereas the clinical strategy at 10 weeks did improve compared to baseline. At 65 dB SPL, DCF performed similarly to the clinical strategy at baseline on the MST, but DCF performed significantly worse compared to the MP control session 5 weeks later. These outcomes reconfirm that, on the SMRT and the MST, learning effects are present over time.

Apart from the presence of learning effects and a mismatch in strategy settings, the somewhat lagging results from the take-home trial were partially attributed to a possible difference in the intracochlear locations of the implant arrays between the pilot study (de Jong et al. 2019a) and the take-home trial (de Jong et al. 2019b), as the latter featured less lateral wall implant arrays (7 out of 17) than the pilot study (9 out of 11). Computational modeling and a recent clinical study (Litvak et al. 2007; Kalkman et al. 2015; Arenberg et al. 2018) revealed that lateral wall arrays are expected to benefit more from focusing strategies than medially placed arrays. In the current study, we adjusted the rate of change for focusing (i.e., the K coefficient in Litvak et al. 2007) on an individual electrode level, based on differences in electrical current consumed between DCF and MP at THL to compensate for the expected electrode array location. A larger K coefficient suggests a larger distance between the electrode and the modiolus, warranting a slower change of σ in the DCF strategy when increasing loudness. It is believed that subjects with higher K coefficients can make better use of loudness cues in dynamic-focused strategies (Litvak et al. 2007; Arenberg et al. 2018). An individual fitting of the K coefficient might allow for a more optimal loudness implementation on an individual electrode level.

The current study aimed to combine the strengths of all previously conducted dynamic focusing studies and objectively control for the learning effects of the psychophysical tests. DCF was compared to a matched, newly fitted, MP strategy in a randomly assigned double crossover design. The goal was to evaluate the effect of DCF compared to MP on speech-in-noise recognition, spectral-temporal testing, temporal testing, and subjective experience when adjusted for learning effects, adaptation period, strategy settings, and K coefficient. Battery life for each strategy was also monitored to evaluate if DCF would lead to impractically short battery life, as occurred in the previous study (De Jong et al. 2019b). We hypothesized that DCF will improve performance in spectro-temporal and speech-in-noise recognition testing over MP at lower loudness levels due to the increased current focusing near THL. At most comfortable level (MCL), we expect at least a comparable performance between DCF and MP, with possible improvements on spectro-temporal testing.

MATERIALS AND METHODS

Study

A single-blinded double crossover take-home trial consisting of four clinical test sessions was conducted, each session preceded by a 3-week adaptation period to the strategy. Each test session lasted 3 hours. The study lasted 12 weeks in total for each participant. Participants were randomly assigned to one of two study protocols: MP-DCF-MP-DCF or DCF-MP-DCF-MP. Participants did not know which strategy they received at each time point. In the last week of each adaptation period, participants filled out the Speech, Spatial and Qualities of Hearing Scale questionnaire (SSQ) (Gatehouse & Noble 2004) to evaluate their subjective experience with the strategy. The study protocol was approved by the Committee for Medical Ethics of Leiden University Medical Centre (P02.106).

Participants

Twenty-seven postlingually deafened individuals (age: 45 to 74 years, mean 64.8, SD 8.6) were fitted with DCF and MP, 13 were eligible to participate in this study based on sufficiently high individual electrode σ values > 0.3 at MCL. Originally $\sigma > 0.5$ was chosen, but this would result in only six participants being eligible for participation. Since THL σ is set to 0.8 or higher, a MCL $\sigma > 0.3$ still allows for a $\sigma > 0.5$ at lower loudness levels.

Each participant was instructed to wear the research strategy daily and as long as possible. Participants were allowed to wear their own clinical strategy when this was necessary (e.g., for phone calls or important meetings when Bluetooth functions were required). The shortest average daily wear time for a participant was 5.5 hours, the longest average daily wear time was 15 hours. Four participants dropped out during the trial. ID14 and ID20 underestimated the intensity of adapting to a new speech encoding strategy during a take-home trial and withdrew in the first week of adaptation. ID12 withdrew from the study because he found the Harmony Research Processor too uncomfortable to wear for prolonged periods of time. ID15 was noncompliant with the given instructions to wear the research processor daily during the adaptation period and was excluded.

Nine participants (age 45 to 72 years, mean 61.4 years, SD 11.0) completed the 12 weeks of the take-home trial. Demographic characteristics are described in Table 1. Four participants were unilaterally implanted with an Advanced Bionics HiRes90K HiFocus 1J electrode array (lateral wall) and four were unilaterally implanted with an Advanced Bionics HiRes90K HiFocus MS (mid-scala) electrode array. ID09 was bilaterally implanted with Advanced Bionics 1J electrode arrays. All participants used HiRes Optima as their clinical strategy. Contralateral hearing loss was > 65 dB HL in all participants; therefore no masking of the contralateral ear during testing was required.

Speech Encoding Strategies

Participants were fitted with the DCF strategy in accordance with previous studies conducted by de Jong et al. (2019a, 2019b). In principle, DCF increases loudness by increasing current spread instead of adding current. Broadening the electrical field increases the perceived loudness while evading device voltage compliance limits.

TABLE 1. Participant characteristics

Participant	Gender	Age (years)	CI Side	Etiology	CI			Deafness (years)	CVC (PH%)	Array	Clinical Strategy	Trial Pulse Characteristics			DCF Settings		
					Allocation	Experience (years)	Pulse Rate (pps)					Pulse Width (µs)	Mean THL σ	Mean MCL σ	Incompatible Electrodes		
ID04	Female	66	AS	Genetic	A	9	15	91	91	1J	Optima	1458.8	52.1	0.93	0.49	-	
ID08	Female	46	ADS	Meningitis	A	8	8	95	95	1J	Optima	1460.8	66.4	1.00	0.64	13,14,15	
ID09	Male	45	AD	Progressive	A	2	35	95	95	MS	Optima	1206.2	43.1	0.85	0.54	2	
ID13	Male	72	AS	Progressive	B	3	23	89	89	MS	Optima	980	35.0	0.94	0.57	2	
ID18	Male	70	AS	Progressive	A	6	44	92	92	MS	Optima	1736	62.0	1.00	0.50	5	
ID19	Female	71	AS	Cholesteatoma	B	3	35	80	80	1J	Optima	1612	62.0	1.00	0.46	6	
ID23	Female	72	AS	Progressive	B	10	15	90	90	1J	Optima	1682.2	64.7	0.98	0.59	-	
ID24	Female	62	AS	Progressive	A	1	3	88	88	MS	Optima	980	35.0	0.95	0.59	-	
ID27	Male	49	AD	Progressive	B	2	25	96	96	MS	Optima	980	35.0	0.98	0.41	2,3,4,11	

AS, left ear; AD, right ear; ADS, both ears; A indicates DCF-MP-DCF-MP; B indicates MP-DCF-MP-DCF; CVC, most recent consonant-vowel-consonant score; MCL, most comfortable level; PH%, percentage of phonemes correct on standardized monosyllabic word test at 65 dB HL; 1J, HiRes90K HiFocus 1J; MS, HiRes90K HiFocus Mid-Scala; pps, pulses per second; MHL, most comfortable level; THL, threshold level; σ , current focusing fraction; incompatible electrode, electrodes fitted with MP instead of DCF in DCF strategy due to $\sigma < 0.3$ at MCL.

Biphasic cathodic first charge-balanced pulse trains were used in both strategies. Pulse rate was dependent on the fitted DCF pulse width. MP pulse width and pulse rate were matched accordingly (Table 1). Strategies were also matched on the number of active electrodes, filter settings, power mode, and radiofrequency level. Participants were fitted with 14-channel configurations of DCF and MP; electrodes 1 and 16 do not have flanking electrodes to allow a DCF configuration. At least 10 electrodes fitted with DCF were required, allowing participants with fewer active electrodes or several “poor” DCF electrodes to partake in the study as well.

Fitting

Both strategies were created using BEPS+ software (Advanced Bionics, Valencia, CA, USA) and the fitting was very similar to that of de Jong et al. (2019b). As a difference, the order of fitting strategies was randomized and individual K coefficients were implemented per electrode for the DCF strategy.

First, THL and MCL were fitted for both strategies. DCF THL σ was fitted to be as high as possible without reaching device compliance limits, with σ options of 0.8, 0.9, and 1.0 per electrode. As mentioned, the minimum σ per electrode at MCL was set at 0.3 to allow enough participants to partake in the study. Mean THL σ was 0.96 (SD 0.06), mean MCL σ was 0.56 (SD 0.16). Participants were excluded if the pulse width exceeded 71 μ s. DCF fitting commenced with THL σ at 0.9 (90% focusing), and σ was increased to 1.0 (100% focusing) if the current remained below 250 μ A at THL. The σ was decreased to 0.8 (80% focusing) when voltage compliance limits occurred or pulse widths exceeded 71 μ s. MCL was attained by decreasing σ in steps of 0.01, increasing the loudness intensity in a controlled setting. Second, both strategies were evaluated and adjusted based on loudness perception, sound quality, and background noise. The modified Potts loudness scale (Potts et al. 2007) was used to identify MCL (number 5 on a scale of 0 to 8). Optimized loudness growth per electrode was attained by calculating and implementing interaction coefficient K per individual electrode. K defines the rate of change for σ depending on the input level of the signal. It is an interaction coefficient that incorporates the contribution from the electric fields generated by the side electrodes to the peak of the electrical activation function when nonzero tripolar compensation is applied (Litvak et al. 2007). A larger K coefficient indicates a slower rate of σ change when increasing loudness. It is believed that a larger electrode-to-modiolus distance corresponds to higher K coefficients and will be expected to receive more benefit from current focusing (Litvak et al. 2007; Kalkman et al. 2015; Arenberg et al. 2018). K coefficients were calculated using the following equation (equation 1) from Litvak et al. (2007):

$$K = \frac{1 - \frac{THL_{MP}}{THL_{DCF}}}{\sigma} \quad (1)$$

where K is the interaction coefficient, THL_{MP} is the number of clinical units required to reach THL in MP, THL_{DCF} is the number of clinical units required to reach THL in DCF, and σ is the focusing used per electrode for the configuration of the DCF strategy: 0.8, 0.9, or 1.0.

The monopolar configuration was fitted according to conventional clinical standards.

Psychophysical Tests

All tests were conducted in the free field in a double-walled, sound-attenuating booth. The participant faced a single loudspeaker at 0° azimuth and a distance of 1 m. The sound levels of each test were calibrated to the designated loudness levels with the manufacturer's provided calibration stimuli for each respective test. The STRIPES makes use of a 1 kHz tone ($rms = 0.1$, the same as the stimuli). The SMRT also included a calibration tone with the same rms as the stimuli. The MST was calibrated with its noise signal as calibration tone. The aMDT was calibrated with the unmodulated stimuli as the calibration tone. Before the start of each test session, the appropriate loudness was confirmed using a handheld sound level meter (Voltcraft SL-200, Hirschau, Germany). During testing, the participants removed their contralateral hearing aid if they wore one. ID09 suffered from severe tinnitus when removing the contralateral cochlear implant processor. In this case, the contralateral processor was set to minimal loudness during testing. Participants were allowed to take a break after each test run and most often took breaks in 1-hour intervals.

Spectro-Temporally Modulated Ripple Test

The SMRT (Aronoff & Landsberger 2013) is a three-interval, three-alternative forced-choice ripple density discrimination task using a 1-up/1-down adaptive procedure that assesses the degree to which a subject can discriminate a ripple stimulus from two reference stimuli of 20 ripples per octave (RPO). Participants initially underwent one full practice run to lessen the effect of test-specific learning during the three formal runs. The test was performed at 45 dB SPL and 65 dB SPL. The outcome is presented in RPO.

STRIPES

The STRIPES (Archer-Boyd et al. 2018) determines the threshold to which subjects are able to discriminate a 1-second upward-sweeping stimulus in reference to two 1-second downward-sweeping reference stimuli of the same density at a rate of five octaves per second. The STRIPES is a ripple glide direction discrimination threshold task. It is a three-interval, two-alternative forced-choice task using a two-up/one-down adaptive procedure. The ripple density was adaptively adjusted during each run of the adaptive procedure. The participants practiced with example trials until they confirmed that they understood the test. These trials were introduced to lessen the effect of test-specific learning during the three formal runs. The test was only performed at 65 dB SPL due to time constraints. The outcome is presented in ripple density.

Amplitude Modulation Detection Test

The aMDT (Won et al. 2011) determines the amplitude modulation detection threshold at which a subject is able to discriminate a 1-second amplitude modulated wideband noise target stimulus from a 1-second wideband noise reference stimulus without amplitude modulation. The aMDT is a two-interval, two-alternative forced-choice test using a two-down/one-up adaptive procedure. Participants underwent at least 10 exemplary trials before each session in which all confirmed that they understood the test. These trials were introduced to lessen the effect of test-specific learning during the three formal runs. The

test was only performed at 65 dB SPL due to time constraints. The outcome is presented as the percentage of modulation relative to 100% modulation.

Matrix Speech-In-Noise Sentence Test

The MST (Hagerman 1982; Luts et al. 2014) is an adaptive test that determines the speech reception threshold (SRT) in speech-weighted noise. The speech reception threshold is the noise level at which a subject understands 50% of a sentence. The Flemish/Dutch test, spoken by a single female talker, comprises 50 unique words consisting of 10 names, 10 verbs, 10 numerals, 10 colors, and 10 objects. Stationary speech-weighted noise generated from the long-term average speech spectrum of the sentence lists was used.

Participants were instructed to repeat the five words and to guess if they were unsure. The responses were manually scored by the experimenter.

Noise level was adaptively varied using a staircase procedure. A reduction in step size was dependent on the number of reversals and the score obtained in the previous trial (Francart et al. 2008). Noise level steps varied from 2 decibels at the start to 0.1 or 0.2 dB at the end of the trial. Answering three or more out of five words correct increased the noise level, two or fewer words correct decreased the noise level. The SRT was estimated based on the average signal-to-noise ratio (SNR) of the final six reversals. For each test session, 3 lists of 20 sentences were randomly selected. Over the course of the study, 12 lists were completed, 6 for each strategy. Lists were never repeated in the same test session. Before testing on each session, 10 randomly selected practice sentences without noise were completed to allow the participant to get accustomed to the test. Speech levels were fixed at 45 dB SPL and 65 dB SPL in randomized order, starting at a SNR of -4 dB. The task was carried out using the APEX 3 strategy (Leuven, Belgium) (Francart et al. 2008) installed on a personal computer. The outcome is presented in dB SNR.

Subjective Rating

To evaluate participants' experience with the DCF and MP strategies, the SSQ (Gatehouse & Noble 2004) was completed at home the day before each test session. Each participant filled out the SSQ 4 times, twice for each strategy. The Spatial Qualities part (i.e., sound localization) of the SSQ was not assessed because it was not a focus of this study.

Battery Life

Participants received four numbered Harmony processor batteries and kept a daily log of battery life and the number of hours that they wore the processor.

Missing Data

SMRT data at 45 dB SPL was missing for ID04, ID08, and ID09 on the first two sessions. ID04 was missing the last two runs of aMDT of session 1 because of an error while saving data. ID08 did not perform the MST on session 1 due to a hardware failure. Lastly, ID24 did not complete the last two runs of the MST at 45 dB SPL due to time constraints.

Statistical Analysis

Statistical analyses were performed using six separate linear mixed-effects models (LMMs), one for each test: SMRT 65 dB SPL, SMRT 45 dB SPL, STRIPES 65 dB SPL, MST 65 dB SPL, MST 45 dB SPL, and aMDT 65 dB SPL. The LMMs were conducted in SPSS Statistics for Windows, Version 26.0 (IBM, Armonk, NY, USA). LMMs control for the within-subject design of the study, its fixed and random effects and allow for the presence of missing data without requiring list-wise deletion. Statistical analysis was completed with mean data per test session. No transformations were carried out. *Strategy* (DCF, MP), *test session* (1 and 2 for each strategy), and their interaction were included as fixed factors in each LMM. Participants' individual intercept and *duration of deafness* were included as random factors, the latter based on literature (Gantz et al. 1993; Green et al. 2007; Moberly et al. 2016). No repeated effect was included due to the small size of the dataset. Satterthwaite approximation was used to estimate degrees of freedom. In each LMM, all convergence criteria were satisfied. In case of significant findings, post hoc analysis was performed with Bonferroni correction for multiple comparisons. The difference between strategies in battery life as well as subjective experience (SSQ) was compared in two-tailed paired samples *t*-tests.

Power Analysis

An a priori power analysis was completed with software package G*power 3.1.9.7 (Faul et al. 2007; Faul et al. 2009). Based on a F-test repeated measures ANOVA with within-subject and between-subject design, an alpha level of $p < 0.05$, a moderate effect size of 0.25, a power of 0.8, two groups, two repeated measurements per strategy and a correlation among repeated measures of 0.8, a sample size of 16 participants was calculated (actual power 0.83). Thirteen participants started the trial. Only nine participants finished the take-home study, although with a higher correlation among repeated measures than initially expected (e.g., .91 for SMRT 65dB between test sessions 3 and 4). The post hoc power analysis revealed a partial η^2 of 0.043 and an actual effect size of 0.21 with an achieved power of 0.73.

RESULTS

Spectro-Temporally Modulated Ripple Test

Figure 1A shows the individual and mean outcomes of DCF and MP on the SMRT at 65dB SPL. When uncorrected, the LMM revealed a significant effect of strategy on SMRT performance at 65 dB SPL [$F(1,24) = 6.7, p = 0.02$]. After Bonferroni correction, the comparison between DCF and MP was no longer statistically significant [$F(1,24) = 6.7, p = 0.1$]. Mean DCF was 3.7 RPO (SEM 0.29, SD 2.2) while mean MP was 3.3 RPO (SEM 0.32, SD 2.3). This resulted in a mean difference of 0.40 RPO benefitting DCF over MP. Five participants improved with DCF over MP (0.31 to 1.41 RPO) and four performed better with MP as the fitted strategy (0.12 to 0.48 RPO).

Figure 1B presents the individual and mean outcomes of DCF and MP on the SMRT at 45 dB SPL. We found no significant effect of strategy on SMRT performance at 45 dB SPL [$F(1,18) = 0.01, p = 0.9$]. Mean outcomes were 4.1 RPO for DCF (SEM 0.28, SD 1.9) versus 4.0 RPO for MP (SEM 0.40,

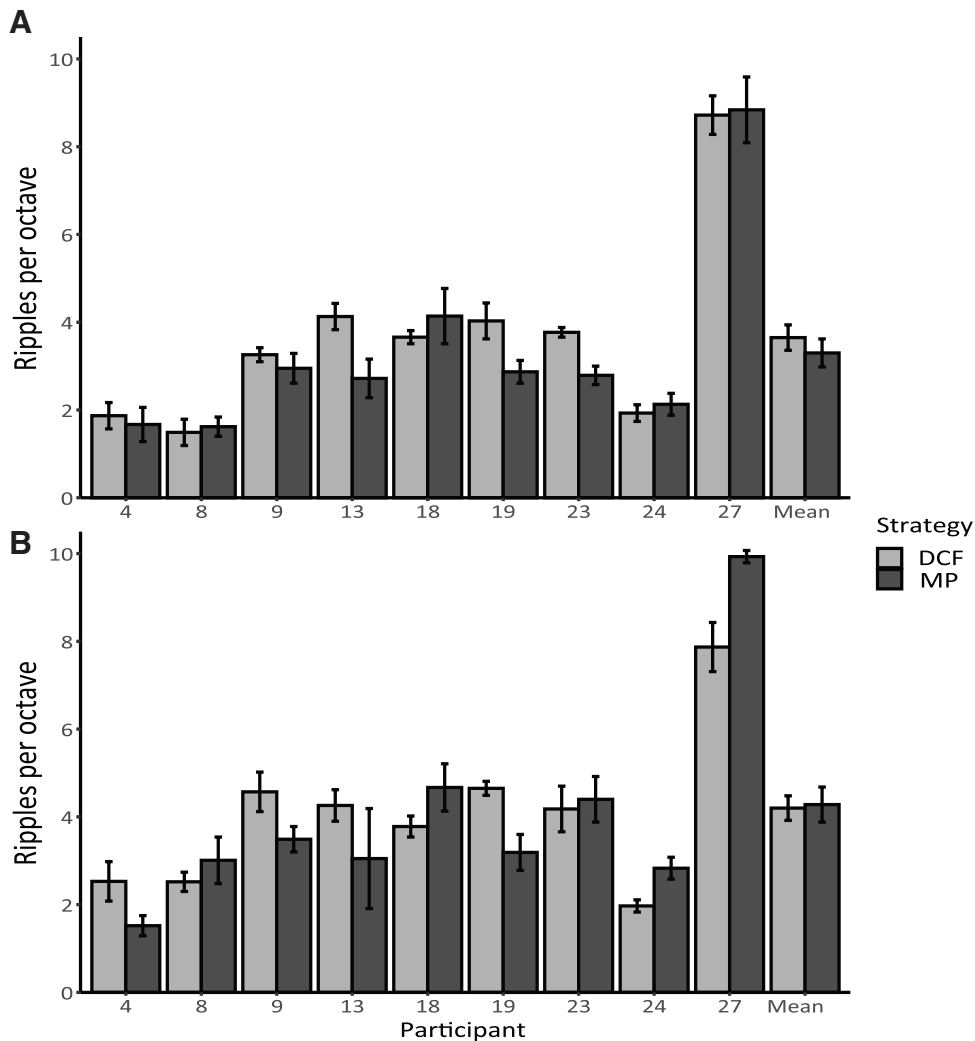


Fig. 1. Individual and overall mean SMRT performance for dynamic current focusing (DCF) and monopolar stimulation (MP) at 65 dB SPL (A) and 45 dB SPL (B). SMRT indicates spectral-temporally modulated ripple test. Error bars represent ± 1 standard error of the mean.

SD 2.7). Four participants improved with DCF, the benefit ranging from 1.01 to 1.46 RPO. Five participants deteriorated with DCF, ranging from -0.23 to -2.06 RPO.

STRIPES

Figure 2A shows the individual and mean outcomes of DCF and MP on the STRIPES at 65 dB SPL. No significant effect of strategy on STRIPES performance was found at 65 dB SPL [$F(1,25) = 0.1$, $p = 0.8$]. DCF and MP mean outcome scores were both rounded to 3.7 ripple density (respectively DCF: SEM 0.21, SD 1.7; MP: SEM 0.23, SD 1.5). Three participants improved with DCF (0.20 to 1.54 ripple density), whereas 6 participants performed better with MP (0.070 to 0.90 ripple density).

In 11 out of 12 measurements, ID13 scored below the minimal meaningful limit of 1.1. Scores below 1.1 ripple density were converted to 1.1. A sensitivity analysis (Chin & Lee 2008; Thabane et al. 2013) revealed that this did not change the significance of the outcomes of the statistical analysis. The exclusion of ID13 in the statistical analysis also had no effect on the significance of outcomes.

Amplitude Modulation Detection Test

The individual and mean results of the DCF and MP on the aMDT are presented in Figure 2B. Lower aMDT scores are considered better performance. We found no significant effect of strategy on aMDT outcome scores [$F(1,23) = 0.001$, $p = 1.0$]. Mean aMDT performance was nearly identical for DCF and MP at -13.49% of modulation (SEM 0.74, SD 5.3) and -13.45% of modulation (SEM 0.86, SD 6.3). The performance of four participants deteriorated with DCF compared to MP (0.2% to 4.8% of modulation), whereas five participants experienced an improvement in performance with DCF over MP (-2.8% to -5.2% of modulation).

Matrix Speech-In-Noise Sentence Test

Lower scores on the MST are considered a better performance. Individual and mean MST results of DCF and MP at 65dB SPL are presented in Figure 3A. At 65 dB SPL, the test revealed no significant effect of DCF on performance compared to MP [$F(1,23) = 0.5$, $p = 0.5$]. Mean SRTs were 2.6 dB SNR for DCF (SEM 0.53, SD 3.8) and 2.2 dB SNR for MP (SEM 0.51, SD 3.7). With DCF, sentence recognition in noise improved in

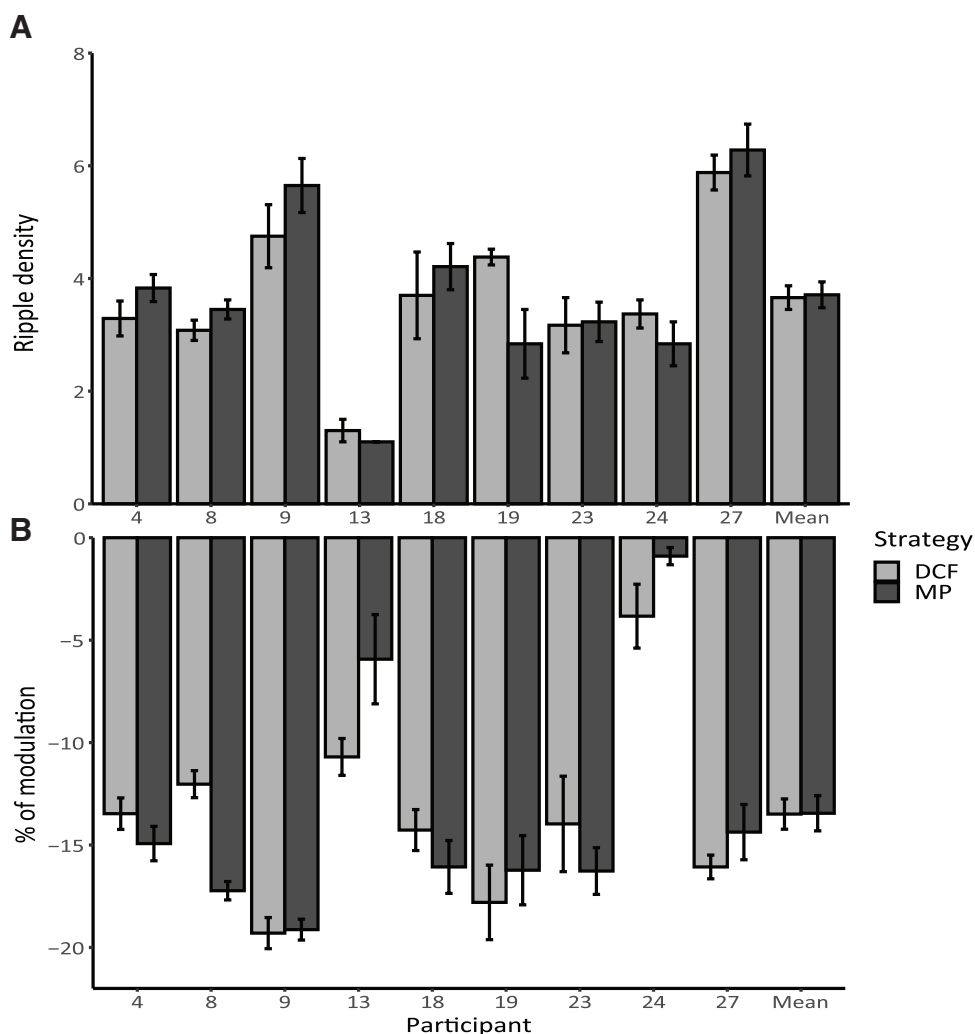


Fig. 2. Individual and overall mean performance for dynamic current focusing (DCF) and monopolar stimulation (MP) on the STRIPES (A) and the aMDT (B) at 65 dB SPL. On the aMDT, lower scores are considered better. aMDT indicates amplitude modulation detection test; STRIPES, spectro-temporal ripple for investigating processor effectiveness. Error bars represent ± 1 standard error of the mean.

five participants (-0.44 to -1.46 dB), whereas it deteriorated in four participants compared to MP (0.65 to 3.90 dB).

Figure 3B shows the individual and mean results of DCF and MP on the MST at 45 dB SPL. The LMM analysis of the MST at 45 dB SPL revealed no significant differences between DCF and MP [$F(1,23) = 0.2, p = 0.6$]. Mean SRT scores for DCF and MP were respectively 3.6 dB SNR (SEM 0.80, SD 5.6) and 3.7 dB SNR (SEM 0.89, SD 6.6). Three participants performed better with DCF (-0.28 to -6.07 dB) while six participants performed better with MP as the fitted strategy (-0.17 to -5.83 dB).

Learning Effects

In all psychophysical tests, there was a significant effect of test session on outcome scores (range $p = 0.002$ to $p = 0.05$). After Bonferroni correction, learning effects on the MST remained significant at both loudness levels [65dB SPL: $F(1,23) = 12.1, p = 0.01$; 45dB SPL: $F(1,23) = 9.5, p = 0.02$]. The lack of significant interaction between *test session* and *strategy* revealed that there was no significant difference in improvement over time between DCF and MP on any of the conducted tests (range: $p = 0.6$ to $p = 0.8$).

Speech, Spatial and Qualities of Hearing Scale Questionnaire

Participants filled out parts 1 and 3 of the SSQ, evaluating the Speech and Quality parts of the questionnaire. Figure 4 presents the individual differences and overall mean outcome scores on the Speech (A) and Qualities (B) subpart of the SSQ. Outcomes were analyzed in a two-tailed paired samples *t*-test. The mean scores for the Speech part were 3.5 for DCF (SEM 0.34, SD 1.5) versus 3.6 for MP (SEM 0.41, SD 1.8). No significant difference was found between DCF and MP on the SSQ Speech part [$t(17) = 0.2, p = 0.8$] and no differences were found between the first and second session of either DCF and MP (respectively DCF1 vs DCF2: $t(8) = 0.4, p = 0.7$; MP1 vs MP2: $t(8) = -0.9, p = 0.4$).

The mean scores of the Qualities part were 4.6 (SEM 0.30, SD 1.3) for DCF and 4.7 for MP (SEM 0.40, SD 1.7). Similar to the Speech part, no significant differences were found between DCF and MP on the Qualities part of the SSQ [$t(17) = 0.4, p = 0.7$] and no differences were found between sessions 1 and 2 of the same strategy (DCF1 versus DCF2: $t(8) = 0.7, p = 0.5$; MP1 versus MP2: $t(8) = -2.2, p = 0.6$).

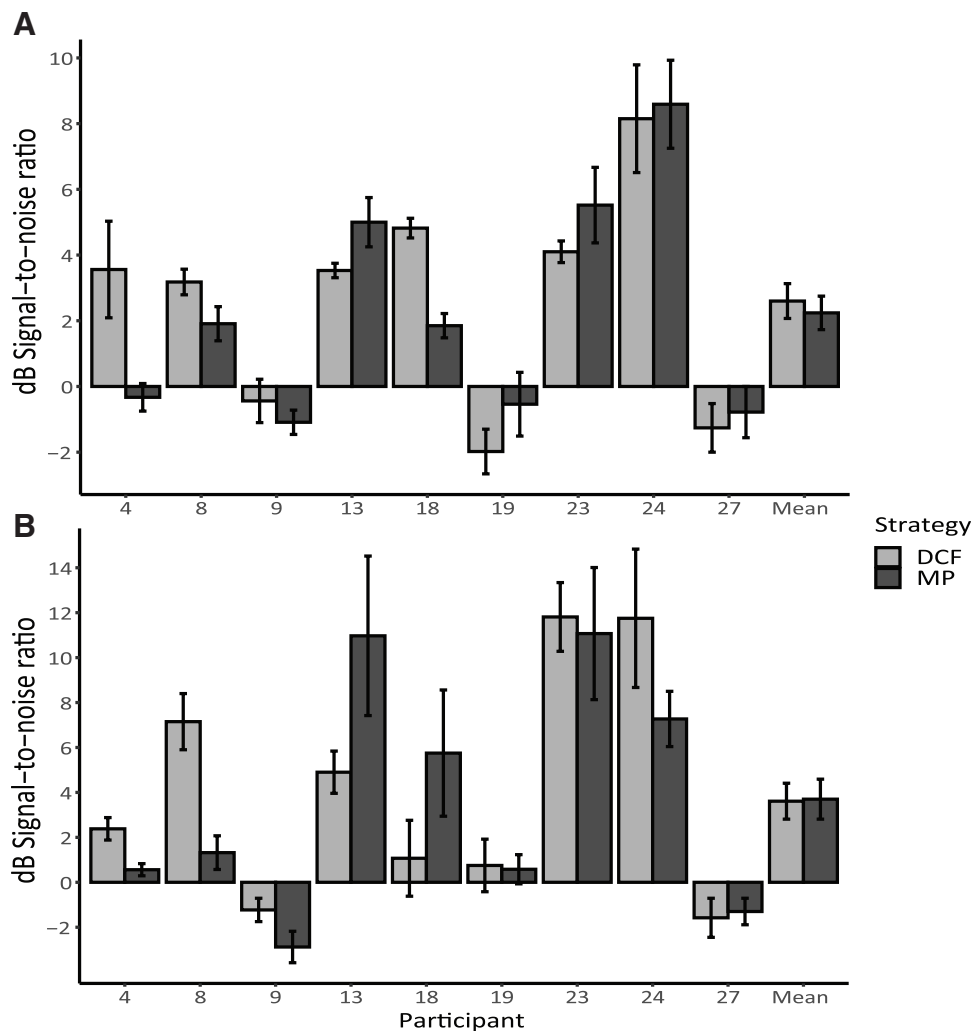


Fig. 3. Individual and overall mean performance for dynamic current focusing (DCF) versus monopolar stimulation (MP) on the matrix speech-in-noise sentence test at 65 dB SPL (A) and 45 dB SPL (B). Lower scores are considered better. Error bars represent ± 1 standard error of the mean.

Battery Life

The mean battery life of the Harmony Research Processor decreased from 10.6 hours for the MP configuration (SD 3.5) to an average of 5.4 hours when using DCF (SD 1.7). A two-tailed paired samples *t*-test revealed a strongly significant difference [$t(59) = 15, p < 0.001$]. This significant effect remains when correcting for multiple comparisons. The average battery life per individual participant is presented in Figure 5.

DISCUSSION

The current trial studied the performance of DCF versus a matched MP configuration over time in a within-subject design. In free field testing, a small improvement (0.40 RPO) was found for DCF over MP on the SMRT at 65 dB SPL. This improvement was no longer significant when corrected for multiple comparisons. No significant differences were found in the MST at soft (45 dB SPL) and conversational loudness levels (65 dB SPL). Similarly, no effect of strategy was found on the temporally-oriented aMDT, the spectro-temporally oriented STRIPES at 65 dB SPL, or the SMRT at 45 dB SPL.

With DCF, battery life was reduced by an average of 5.1 hours compared to MP (i.e., by 48%). As the results show, with the exception of the slightly improved SMRT scores at conversational loudness and a greatly reduced battery life, DCF performs similarly to MP on spectral, temporal, and speech-in-noise recognition tests.

There is a theoretical basis for the larger benefits of current focusing for lateral wall arrays compared to mid-scalar arrays (Kalkman et al. 2015; van der Jagt et al. 2016) due to the larger area for electrical field shaping. Notably, the DCF pilot study (de Jong et al. 2019a) consisted of 9 out of 11 subjects with a HiRes 90K HiFocus 1J electrode array. An improvement was found for DCF over MP with SMRT in the acute setting at 45 dB SPL. This improvement was not apparent at 45 dB SPL in our current study. The current study consisted of five HiRes 90K HiFocus MS (mid-scalar) arrays and four HiRes 90K HiFocus 1J (lateral wall) arrays, where no correlation was found between implant array type and performance on any of the psychophysical tests. Implant type was therefore not included in the most parsimonious LMMs.

Previous studies have reported that a reduction in current spread compared to MP is negligible at lower σ (Bierer & Middlebrooks 2002; Bonham & Litvak 2008). Landsberger et al.

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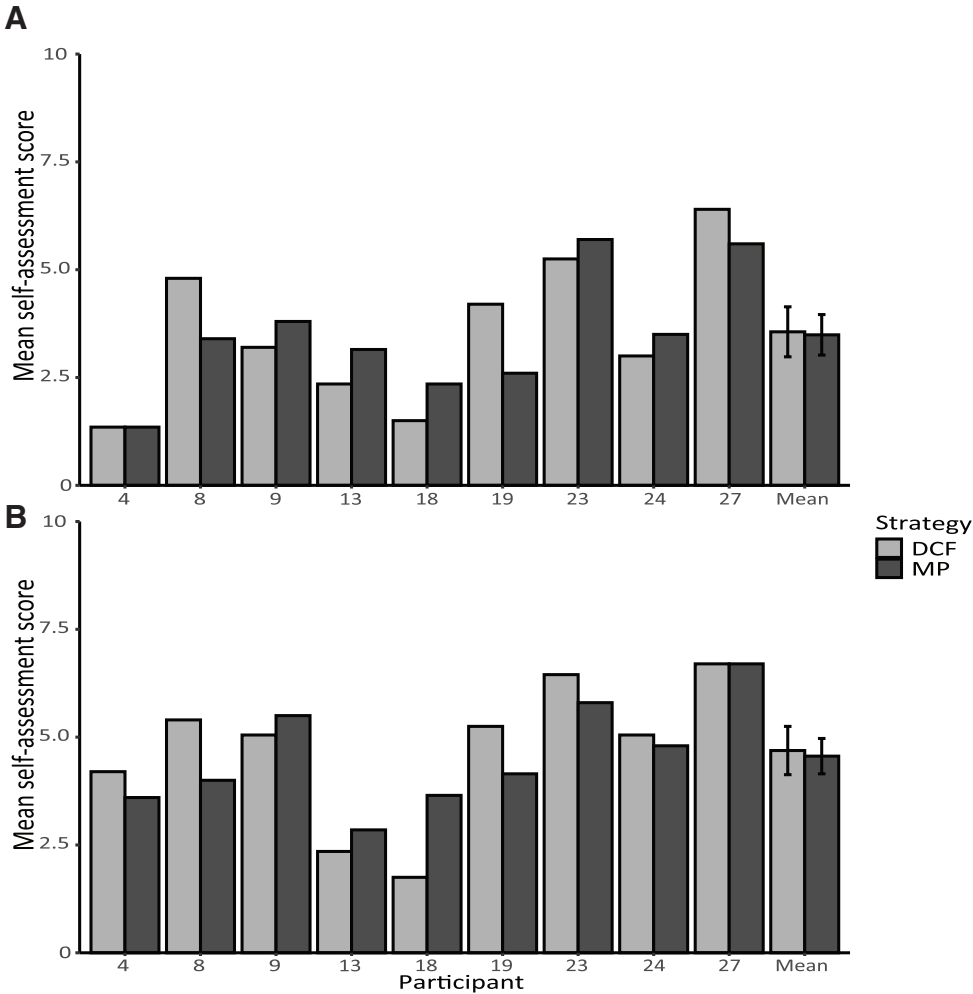


Fig. 4. Individual and overall mean performance for dynamic current focusing (DCF) and monopolar stimulation (MP) on the Speech (A) and Qualities (B) parts of the Speech, Spatial and Qualities of Hearing Scale questionnaire. Error bars represent ± 1 standard error of the mean.

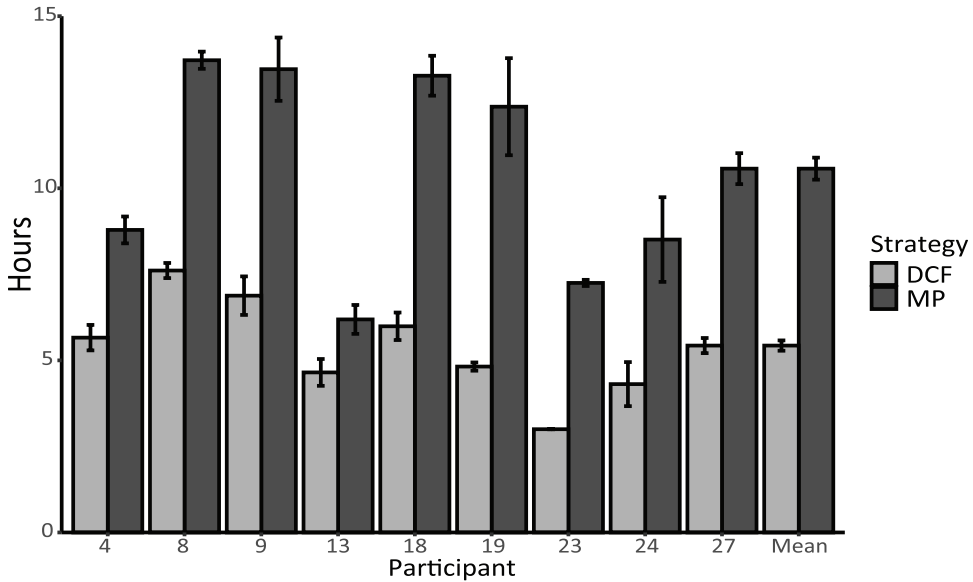


Fig. 5. Mean individual and overall battery life for dynamic current focusing (DCF) and monopolar stimulation (MP). Error bars represent ± 1 standard error of the mean.

(2012) argued that σ required to be > 0.5 to effectively reduce current spread compared to MP, which was later confirmed by Srinivasan et al. (2013). In de Jong's pilot study (2019a), the participants had a sufficiently high mean σ of 0.88 (0.8 to 1.0) at THL and 0.49 (0.21 to 0.74) at MCL. The take-home trial that followed (De Jong et al. 2019b) found a significant difference between DCF and MP in spatial resolution compared to baseline, but not compared to the control measurement 5 weeks later. However, mean σ had decreased to only 0.17 at MCL and even included negative focusing in its range (−0.22 to 0.39). Negative focusing means that flanking electrodes had the same polarity as the center electrode contact. The mean σ of this study was 0.96 at THL and 0.53 at MCL. However, to reach sufficiently high σ values, more than half of the participants were excluded at baseline during fitting (14 out of 27). The high degree of current focusing in this study strengthens the claim that the uncorrected significant effect on the SMRT at conversational loudness could be attributable to the narrower current spread of DCF. To negate this claim, the SMRT did not reveal significant differences between the two strategies at 45 dB SPL, where it was most expected. The improvement in spatial resolution on the SMRT at conversational loudness would be expected to also be apparent on the STRIPES, which was not the case. This could possibly be explained by the tests measuring different warranted or spurious cues (e.g., loudness cues and noticeable changes in the spectral edges), as has been debated in recent literature (Narne et al. 2016; Archer-Boyd et al. 2018; Narne et al. 2019). It could also signify that the absence of a significant effect on the STRIPES and the small distinguishable effect on the SMRT means that the clinical relevance of the findings is marginal. A third explanation could be that the psychophysical tasks conducted in this study are not accurate enough to correctly measure a small difference in performance between strategies and would therefore be suboptimal for use in repeated testing. All outcomes present evidence of at least small to considerable within-subject variation on all psychophysical tests.

At some point, all participants mentioned that they had difficulties with the long duration of the study. Participants particularly missed the Bluetooth function to connect their cochlear implant to other devices, a function present on their clinical processor but missing on the Harmony research processor. Also, not being able to use beamformers with the research strategies was noted as an annoyance. These sentiments can explain the low overall scores for both strategies on the SSQ. Whether the reported scores are low due to the sound quality of both newly fitted strategies or whether they are a measure of their general perception of speech and sound is not known. Participants were not required to fill out the SSQ with their clinical strategy as a reference. De Jong et al.'s (2019b) comparison of DCF with a subject's clinical strategy revealed no significant differences between speech ratings (DCF: 4.7; clinical: 5.2) ($p = 0.1$), but did reveal a deterioration in the Qualities section of the SSQ from 6.2 to 5.5 ($p = 0.04$). A large study by Moulin and Richard (2016) with 230 hearing-impaired listeners (without cochlear implants) found the average scores to be 5.9 on the Speech part and 7.2 on the Qualities part. Mertens et al. (2013) found lower SSQ scores in self-assessments of cochlear implant users. The overall score on the SSQ was 4.25 (SD 1.65) based on 54 participants. The average mean scores on the Speech, Spatial, and Qualities items were 3.92 (SD 1.63), 3.35 (SD 1.19), and 5.17 (SD 0.91), respectively. Taking into account that new strategies

were used, scores of 3.5 and 3.6 for the Speech part and 4.6 and 4.7 for the Qualities part found in our current study are roughly consistent with Mertens et al. (2013). In future studies, we will include the SSQ of participants' clinical strategies at baseline so the subjective experience of experimental studies can be directly compared with a participant's current clinical strategy.

This study found a learning effect to be present in all of the psychophysical tests. Similar results were found in a recent study (de Jong et al. 2018) in which subjects continued to improve on the SMRT and the aMDT up to 6 weeks after baseline measurements. Speech-in-noise recognition was most prone to learning over time, as has already been well described in the literature (Kollmeier et al. 2015; Willberg et al. 2020). When evaluating strategies, we believe repeated testing is preferred over acute testing. The presently used repeated crossover design visualizes and accounts for these learning effects. This design also allows the insertion of adaptation periods to a new strategy. The disadvantage of this design is the extra burden it places on participants and their willingness to participate in current and future studies. We recommend weighing the total duration of the study with its expected burden on participants' daily life.

With nine participants, the current study sample is too small to draw definite conclusions. The repeated adaptation time of three weeks was relatively short to manage the total duration of the study. We did not control for the environments participants encountered at home, which means participants probably encountered different listening situations and varying amounts of time within those environments. Notwithstanding, taking the previous dynamic focusing literature into account (Arenberg et al. 2018; de Jong et al. 2019a, 2019b), increasing evidence is found that dynamic focusing does not significantly improve speech-in-noise recognition in cochlear implant users compared to MP. Some improvement was found in spatial selectivity, but not at lower loudness levels where it was most expected. Nevertheless, no significant deterioration was found in any of the psychophysical tests (speech-in-noise recognition, spectrally, or temporally) or on the subjectively rated SSQ. However, battery life was greatly reduced for DCF in comparison with MP stimulation. Our results reveal that DCF is a functional alternative to MP but it has not been shown to improve speech-in-noise recognition on group-level.

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Address for correspondence: Johan H. M. Frijns, ENT Department, Leiden University Medical Centre, P.O. Box 9600, 2300 RC Leiden, The Netherlands. E-mail: J.H.M.Frijns@lumc.nl

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