PLACE-BASED MAPPING WITH ELECTRIC-ACOUSTIC STIMULATION

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ABSTRACT

Margaret Tatum Dillon: Place-Based Mapping with Electric-Acoustic Stimulation
(Under the direction of Emily Buss)

The goals of this dissertation were to understand the influence of electric frequency-to-place mismatches on the speech recognition of listeners of electric-acoustic stimulation (EAS) and whether listeners would experience better speech recognition with maps derived from a strict place-based mapping as compared to alternative mapping procedures. Current default EAS mapping procedures do not account for the individual variation in electrode array placement relative to cochlear tonotopicity, resulting in electric frequency-to-place mismatches. The strict place-based mapping procedure assigns the electric filter frequencies to match the cochlear place frequencies for electrodes in the low-to-mid frequency region and distributes the remaining high-frequency information across electrodes in the basal region. The rationales for this procedure are that eliminating mismatches will improve speech recognition since 1) critical speech information is provided by the mid-frequencies and 2) better spectral resolution of low-frequency cues may support better performance in noise. EAS simulation studies find acute masked speech recognition is significantly better with strict place-based maps as compared to maps with spectral shifts. For the present work, the first experiment evaluated the effectiveness of the strict place-based mapping procedure to an alternative full-frequency place-based mapping procedure using simulations of short electrode arrays at shallow angular insertion depths. Recipients of short arrays (e.g., ≤ 24 mm) may experience limited benefit with strict place-based maps since speech information below the frequency of the most apical electrode is discarded. The full-frequency place-based map would provide more low-frequency information yet present spectral shifts for the electrodes below the 1 kHz cochlear region. For the EAS simulations, performance with the strict map remained stable across cases, while performance with the full-frequency map improved with decreases in AID. The second experiment assessed the pattern of speech recognition acclimatization for EAS users listening with either a strict place-based map or default map. Poorer performance was observed for EAS users with larger magnitudes of electric mismatch out to 6-months post-activation. Taken together, the results from this dissertation suggest that eliminating electric frequency-to-place mismatches such as with the strict place-based mapping procedure supports better early speech recognition for EAS users than alternative mapping procedures.

To my family and friends whose love and encouragement made this possible.
To the study participants who gave their time and energy to help us understand how to help individuals with hearing loss hear their best.

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My interest in clinical research began when I was doctorate of audiology graduate student training under Dr. Marcia Clark Adunka. She invited me to participate in her clinical research discussions with Dr. Emily Buss. Dr. Adunka was passionate about providing the best care for her patients with cochlear implants and would consistently question how to improve upon evidence-based practice. Dr. Buss would discuss the mechanisms that may have contributed to Dr. Adunka’s clinical observations and recommend strong study designs that would best answer her questions. I wanted to be the combination of these two women – a clinician-scientist who investigated methods to improve patient outcomes. Their mutual respect and collaboration impacted the way I view how clinicians and researchers should interact to advance science and improve the treatment of the patients who trust us with their care.

When I decided to pursue the PhD, I wanted Dr. Buss to take me on as her trainee. Her brilliance and ingenuity are unmatched. I knew with her mentorship that I would be able to ask stronger questions, design more thorough experiments, and contribute to our team and field in a more meaningful way. It is energizing to talk about new ideas and data with her, which were some of my favorite moments during this process. Dr. Buss also helped me develop skillsets that would make me be more independent as a researcher. She is also incredibly kind. I am thankful for all she has done to support me professionally and personally. She has made me a stronger scientist and shaped the way I interact with colleagues and mentor trainees. I am thankful to have been trained by both Drs. Adunka and Buss during my clinical and research careers.

During my clinical coursework, I had the unique opportunity to work with Dr. Charles Finley. At the time, there was only one course on cochlear implants. The course content did not allow for an in-depth review of signal coding and I did not feel confident in my mapping decision-making since I did not know what was happening behind the scenes in the software. Dr. Finley allowed me to complete an independent study with him. He assigned specific readings and we met weekly to discuss my impressions and questions. It was a gift to have that one-on-one interaction with someone who impacts the field in a major way. Learning from him made me realize I wanted to investigate mapping manipulations that would improve the sound quality and ultimately the performance of our patients with cochlear implants, and I am thankful for that opportunity.

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Finally, thank you to the participants with normal hearing and with hearing loss who contributed to this work. An aim of this line of research is to help patients hear their best. Thank you for dedicating your time and energy to help us understand how we can better serve patients with hearing loss.

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LIST OF ABBREVIATIONS AND SYMBOLS

AID	angular insertion depth
α	significance level
~	approximately
ANSI	American National Standards Institute
©	copyright
CF	center frequency
CI	cochlear implant
CI-full	cochlear implant with full-frequency place-based map
CI-strict	cochlear implant with strict place-based map
CNC	Consonant-Nucleus-Consonant
CT	computed tomography
cu	current unit
d	Cohen’s d
dB	decibel
º	degrees
DF	degrees of freedom
E	electrode
EAS	electric-acoustic stimulation
EAS-full	electric-acoustic stimulation with a full-frequency place-based map
EAS-strict	electric-acoustic stimulation with a strict place-based map
F	F-statistic
FIR	finite impulse response
>	greater than

≥	greater than or equal to
HL	hearing level
Hz	Hertz
IRB	Institutional Review Board
LF	lower filter frequency
LFPTA	low-frequency pure-tone average
lme	linear mixed effects
LMM	linear mixed model
kHz	kilohertz
<	less than
≤	less than or equal to
MATLAB	matrix laboratory; a computing environment and programming language
MCL	maximum comfortable loudness
mm	millimeters
NAL-NL1	National Acoustic Laboratories' nonlinear fitting procedure, version 1
p	p-value; significance level
%	percent correct
Ph.D.	Doctor of Philosophy
R	R statistical software
RAU	rationalized arcsine unit
SD	standard deviation
SE	standard error
SG	spiral ganglion
SNR	signal-to-noise ratio

SPL	sound pressure level
T	threshold
t	*t*-statistic
UNC	The University of North Carolina at Chapel Hill

CHAPTER 1: INTRODUCTION

Cochlear implant (CI) recipients with residual acoustic hearing in the implanted ear are fit with acoustic amplification and a CI in the same ear, a configuration referred to as electric-acoustic stimulation (EAS). Better performance is typically observed with EAS than with a CI alone (Dillon et al., 2015; Dunn et al., 2010; Gantz et al., 2009; Gifford & Dorman, 2012; Gifford et al., 2013, 2014; Pillsbury et al., 2018; Rader, Fastl, & Baumann, 2013), which is likely due to access to acoustic low-frequency cues, such as the fundamental frequency, which can support better speech recognition in noise. However, the benefit of EAS compared to the CI-alone varies widely across individuals (Gantz et al., 2016; Pillsbury et al., 2018). The individual differences in the performance of EAS users could be due in part to differences in duration of hearing loss, age at implantation, and degree and configuration of residual acoustic hearing in the implanted ear (Gantz et al., 2016). The variation in performance could also be due in part to the wide variability in angular insertion depth (AID) of the electrode array across CI recipients (Canfarotta et al., 2020; Landsberger et al., 2015) and the resulting variability in the cochlear place of stimulation. The default mapping procedures for CI-alone and EAS device do not account for the patient-specific variability in the electrode array location, which can often result in discrepancies between the electric filter frequencies assigned to a particular electrode and the normal cochlear place frequencies at the location of the electrode, known as electric frequency-to-place mismatches. There is longstanding evidence of the negative influence of frequency-to-place mismatches on speech recognition for listeners of CI-alone simulations and CI-alone devices (Başkent & Shannon, 2003, 2005; Fu, Shannon, & Galvin, 2002; Shannon, Zeng, &

Wygonski, 1998), however, the influence on the speech recognition for EAS users is less clear. The primary aims of the present experiments were to understand the influence of electric frequency-to-place mismatches for listeners of EAS and whether listeners would experience better speech recognition with maps derived from a strict place-based mapping as compared to alternative mapping procedures. Understanding the influence of electric mismatches and the benefit of individualizing electric filter frequencies is of high clinical importance since approximately 60% of EAS users experience electric frequency-to-place mismatches of ½ octave (6 semitones) or more (Canfarotta et al., 2020).

Mapping of electric filter frequencies: CI-alone devices

Multi-channel electrode arrays take advantage of the tonotopic organization of the cochlea by distributing low-frequency speech information to apical electrodes and high-frequency speech information to basal electrodes. The electric filter frequencies for individual channels determine the frequency range for the speech information presented by specific electrodes. For CI-alone devices, default mapping procedures aim to provide the listener with the full speech frequency range (e.g., 70-8500 Hz) in order to support optimum speech recognition. The speech frequency range is logarithmically distributed across the active channels. The default mapping procedure does not account for the patient-specific variability in the electrode array location, which is influenced by the individual cochlear morphology, electrode array design/length, and surgical approach (Nordfalk et al., 2016; O'Connell et al., 2016, 2017). Variable magnitudes of electric frequency-to-place mismatches are observed for CI-alone users listening with default maps (Canfarotta et al., 2020; Landsberger et al., 2015).

Studies of CI-alone simulations and CI-alone users demonstrate that acute speech recognition is better with maps that align the filter frequencies with the cochlear place frequencies as compared to maps with large frequency-to-place mismatches (Başkent & Shannon, 2003, 2005; Fu et al., 2002; Shannon et al., 1998). Tasks of vowel recognition have been demonstrated as sensitive measures to assess the influence of electric frequency-to-place mismatches on speech recognition (Başkent & Shannon, 2003, 2005; Fu et al., 2002) as compared to tasks of consonant recognition (Başkent & Shannon, 2003; Fu et al., 2002). Fu and colleagues (2002) proposed that the different pattern of results between tasks of vowel and consonant recognition was due to the limited effect of the frequency-place relationship on the temporal pattern needed for consonant recognition as compared to the significant effect of the frequency-place relationship on the spectral pattern needed for vowel recognition. While performance with acute listening experience with spectrally shifted maps has been observed to be poorer than with aligned maps, CI-alone users and participants with normal hearing listening to CI-alone simulations demonstrate the ability to acclimate with extended listening experience (Faulkner, 2006; Fu et al., 2002, 2005; Fu & Galvin, 2003; Li & Fu, 2007; Li, Galvin, & Fu, 2009; Reiss et al., 2007, 2014; Rosen, Faulkner, & Wilkinson, 1999; Sagi et al., 2010; Smalt et al., 2013; Svirsky et al., 2004, 2015b; Vermeire et al., 2015).

Default EAS mapping procedures

Default mapping procedures for EAS devices also aim to provide the listener with the full speech frequency range, with an additional step of dividing the frequency range between the acoustic and electric outputs. Default EAS mapping procedures use the patient's acoustic unaided hearing detection thresholds in the implanted ear to determine the output of the acoustic component and the lowest frequency presented by the electric component, referred to as the low-frequency cutoff. The low-frequency cutoff is defined as the frequency at which unaided detection thresholds in the implanted ear exceed a criterion level (e.g., 70 dB HL, see Gifford et al., 2017), above which acoustic stimulation is less effective. To minimize spectral gaps in the signal provided to the listener, speech information above the low-frequency cutoff is presented electrically and distributed logarithmically across active electrodes – irrespective of their intracochlear location. Karsten and colleagues (2013) demonstrated that this EAS mapping procedure supports better speech recognition compared to procedures that present the low-frequency speech information both acoustically and electrically, or procedures that leave a gap between the highest frequency associated with audible acoustic stimulation and the lowest frequency associated with electric stimulation.

Use of the CI recipient's unaided detection thresholds allows for some degree of individualized EAS mapping which provides an effective representation of the acoustic information (Dillon et al., 2014; Vermeire et al., 2008); however, default EAS mapping procedures do not account for patient-specific variability in electrode array location. Short (e.g., ≤ 24 mm) electrode arrays are typically used for CI candidates with normal-to-moderate low-frequency thresholds due to the increased likelihood of hearing preservation with less trauma to the apical cochlear region compared to longer arrays (Gantz et al., 2016; Suhling et al., 2016; Wanna et al., 2018). Recently, hearing preservation has also been observed for CI recipients of long (e.g., 31.5 mm) arrays with more flexible designs than earlier generations (Helbig et al., 2011; Hollis et al., 2021; Mick et al., 2014). Electric frequency-to-place mismatches are prevalent in EAS users due to the wide variability in AID across and within electrode arrays (Canfarotta et al., 2020) and variability in residual acoustic hearing (Gantz et al., 2016; Pillsbury et al., 2018).

The spectral shifts associated with electric frequency-to-place mismatches have been shown to negatively influence vowel recognition in quiet for participants with normal hearing listening to EAS simulations (Fu, Galvin, & Wang, 2017). Considering the presence of the low-frequency acoustic information, it is unclear whether electric frequency-to-place mismatches will also negatively influence speech recognition in noise. The acoustic hearing may serve as an anchor to cochlear place, making it challenging to recognize speech in noise when combined with a spectrally shifted map. Alternatively, the acoustic information may provide low-frequency cues that aid in deciphering the spectrally shifted electric information, which could reduce the negative influence of electric frequency-to-place mismatches for EAS users. It is also unclear whether the patterns of performance observed for EAS simulations are the same as for actual EAS users.

Place-based EAS mapping procedures

The present experiments investigate speech recognition performance when listening to maps derived from a place-based mapping procedure that incorporates AID and the associated cochlear place frequency into EAS mapping to eliminate electric frequency-to-place mismatches. Initial investigations in CI-alone users or CI-alone simulations demonstrated better speech recognition with maps that approximately matched the cochlear place frequency, based on linear insertion depth of the electrode array, as opposed to maps that presented spectrally-shifted information (Başkent & Shannon, 2003, 2004, 2005; Dorman, Loizou, & Rainey, 1997; Fu & Shannon, 1999a; Li & Fu, 2010). More recently, use of intra-operative and post-operative imaging has supported more accurate estimates of AID and the cochlear place frequency associated with individual electrodes (Canfarotta et al., 2019; Noble et al., 2012, 2014). The mapping procedure used in the present experiments, termed *strict place-based EAS mapping*, uses the post-operative computed tomography (CT) image to estimate AID for each electrode, calculates the cochlear place frequency associated with each electrode, and identifies any electrodes within the functional acoustic hearing region (i.e., ≤ 65 dB HL). The procedure aligns the speech information for electrodes up to at least the 3 kHz cochlear region; the remaining high-frequency information is distributed across the channels for the electrodes in the basal region. The rationale for aligning the low-frequency information is that providing better spectral resolution of these cues may support better speech recognition in noise (Jin & Nelson, 2010; Qin & Oxenham, 2003). The rationales for distributing the high-frequency information across basal electrodes as opposed to deactivating electrodes in the region above the upper filter frequency limit for the device (i.e., 8.5 kHz) are: 1) listeners can tolerate spectral shifts of high-frequency information when the mid-frequency information is aligned (Başkent & Shannon, 2007), and 2) most high-frequency speech cues are not spectrally discrete (e.g., voiceless fricatives). The 3-kHz criterion was selected due to the importance of speech information in the 1-3 kHz region (ANSI, 1997; Warren et al., 1995), although some data suggest that the band importance function may vary across individual CI recipients (Bosen & Chatterjee, 2016).

In addition to eliminating electric frequency-to-place mismatches, the present place-based mapping procedure aims to limit potential peripheral electric-on-acoustic masking, which is when electric stimulation in the region of acoustic hearing interferes with the neural response to acoustic stimulation. For CI recipients of electrode arrays close to or within the region of functional acoustic hearing, the electric current spread from apical electrodes may mask low-frequency acoustic cues (Imsiecke et al., 2020a, 2020b; Kipping, Krüger, & Nogueira, 2020; Krüger, Büchner, & Nogueira, 2017; Lin et al., 2011). This particular scenario is increasingly relevant as hearing preservation has been shown in CI recipients of long (e.g., 31.5 mm), flexible lateral wall arrays (Hollis et al., 2021; Mick et al., 2014; Usami et al., 2014). The default EAS mapping procedures do not include methods to limit electric-on-acoustic masking. For the present place-based mapping procedure, the current levels for electrodes identified to be within the region of functional acoustic hearing are reduced below the listener's detection to attempt to minimize peripheral electric-on-acoustic masking.

A consideration of the present strict place-based EAS mapping procedure is that it may introduce a spectral gap in the provided frequency information. A frequency gap would occur when the most apical electrode is positioned basal to the cochlear place of functional acoustic hearing. Some data suggest that a gap between acoustic and electric information is detrimental for speech recognition with EAS (Karsten et al., 2013), but tonotopicity was not considered in that prior research. That is, the AID of the electrode array and the electric frequency-to-place mismatches with the evaluated filter frequencies were not included and may have influenced the findings. Short electrode arrays and shallow insertion depths generally confer the highest rate of successful hearing preservation (Gantz et al., 2016; O'Connell et al., 2017; Suhling et al., 2016), and thus short arrays are selected most often for hearing preservation cochlear implantation cases. As such, the apical electrode is most often positioned basal to the region of residual hearing for EAS users (Canfarotta et al., 2020). A *strict* place-based EAS mapping procedure may create large gaps in frequency information for CI recipients with electrode arrays at shallow AIDs. Recently EAS simulation studies demonstrate that listeners can tolerate spectral gaps between the acoustic and electric frequency information when listening with place-based maps (Dillon et al., 2021a; Fu et al., 2017; Willis et al., 2020). For example, Willis and colleagues (2020), reported better speech recognition with simulations of place-based maps than spectrally shifted maps, even with a spectral gap between 600 and 1200 Hz with the place-based map. It is possible that the cost associated with a larger spectral gap in the speech signal or with gaps in the critical speech frequency region (e.g., 1.5 kHz; Warren et al., 1995) would outweigh the benefits of strict place-based mapping in EAS users with shallow AIDs, resulting in better speech recognition with electric frequency-to-place mismatches in some EAS users.

The effectiveness of the present strict place-based mapping procedure as compared to the default EAS mapping procedure on speech recognition was first evaluated in simulation studies (Dillon et al., 2021a, 2022). The experiment modeled the cochlear place frequencies of an example 24-mm electrode array recipient, since a 24-mm electrode array is preferred at the study site for cases with normal-to-moderate low-frequency acoustic hearing. Participants listened to simulations of default versus place-based maps and completed a task of masked sentence recognition, which provides richer context cues more similar to those encountered in natural communication than tasks of vowel recognition. The place-based map introduced a spectral gap in the acoustic and electric frequency information (i.e., 250-550 Hz). Significantly better acute speech recognition was found with the place-based map (550-8500 Hz) than the default map (250-8500 Hz). For example, mean performance was 38% with the default map and 58% with the place-based map at the 10 dB signal-to-noise ratio (SNR). The implication was that aligning the electric filters to cochlear tonotopicity supports better speech recognition than providing the full speech spectrum with spectrally shifted maps. What remained unclear is whether this pattern of performance would be observed for recipients of electrode arrays at shallower AIDs. For those cases, the strict place-based mapping procedure would discard more low-frequency information than simulated by Dillon et al. (2021a; 2022). Individuals with electrode arrays at shallow AIDs may benefit from an alternative place-based mapping procedure that aims to provide more low-frequency information than the strict place-based mapping procedure.

An alternative to a *strict* place-based map would be a *full-frequency* place-based map that provides the listener with the full-frequency spectrum by aligning the mid-frequency information (e.g., 1-3 kHz) to the cochlear place frequency and distributing the low-frequency information across the apical electrodes and high-frequency information across basal electrodes, irrespective of place. Better speech recognition may be observed with a *full-frequency* map since the listener would have the benefit of aligned information in the critical speech frequency region in addition to access to the full speech spectrum. Conversely, it may be challenging for EAS users to adjust to spectral shifts in electrically represented low-frequency information when both lower frequency acoustic information and higher frequency electric information are aligned to cochlear place. This prediction is supported by EAS simulation studies that demonstrate better performance with place-based maps than spectrally shifted maps, even with large frequency information gaps (i.e., .6 – 1.2 kHz) between the acoustic and electric outputs with strict place-based maps (Fu et al., 2017; Willis et al., 2020). Those previous EAS simulations presented frequency-to-place mismatches across the entire range of input frequencies for the spectrally shifted maps. In contrast, the present full-frequency place-based mapping procedure aligns the mid-frequency information with cochlear place and intentionally shifts lower and higher frequency information to provide more of the speech spectrum.

Present research

The *purpose* of the present research was to evaluate whether a strict place-based mapping procedure supports better speech recognition as compared to a default mapping procedure or a full-frequency place-based mapping procedure. Speech recognition performance was evaluated for participants with normal hearing who listened to EAS simulations and actual EAS users. Acute speech recognition was first compared with a *strict* versus *full-frequency* place-based map using EAS simulations of short electrode arrays at shallow AIDs. Next, the speech recognition of

EAS users was evaluated as a function of electric frequency-to-place mismatches during the first 6 months of listening experience.

For the first experiment, acute speech recognition was evaluated in participants with normal hearing listening to vocoded speech. The vocoder simulations extracted the envelope of the speech stimulus within each analysis band and applied it to a noise-band carrier; the frequency content of the noise-band carrier controlled the place of transduction via natural tonotopicity of the normal-hearing cochlea. The *strict* place-based mapping procedure aligned low-to-mid frequency information to cochlear place, an approach that may entail a spectral gap. The *full-frequency* place-based mapping procedure aligned the mid-frequency information to the cochlear place frequency and distributed the low-frequency information across the apical electrodes, irrespective of place, to provide the listener with more speech information than would be provided by the strict place-based mapping procedure. The hypotheses were: 1) better speech recognition would be observed with the *full-frequency* place-based map as compared to the *strict* place-based map for simulations of electrode arrays at shallow AIDs (e.g., 335º), and 2) better speech recognition would be observed with the *strict* place-based map as compared to the *full-frequency* place-based map for simulations for electrode arrays at deeper AIDs (e.g., 460º). Performance with the different map configurations was evaluated in participants with normal hearing listening to EAS simulations to assess the potential risks and benefits of place-based mapping prior to implementation with EAS users.

Experiment 2 built upon the above EAS simulation studies by investigating the effectiveness of place-based mapping in EAS users and the influence of electric frequency-to-place mismatches on early speech recognition. Participants were randomized to listen with either a default or strict place-based map at initial device activation and were evaluated acutely and at the 1-, 3-, and 6-month follow-up visits. The hypotheses were: 1) EAS users with minimal electric frequency-to-place mismatches would experience better acute speech recognition and more rapid performance growth than EAS users with larger electric frequency-to-place mismatches, and 2) the performance of EAS users with the default map would be negatively correlated with the magnitude of the electric frequency-to-place mismatch.

CHAPTER 2: PLACE-BASED MAPPING OF LOW-FREQUENCY SPEECH INFORMATION FOR SIMULATIONS OF COCHLEAR IMPLANT AND ELECTRIC-ACOUSTIC STIMULATION DEVICES AS A FUNCTION OF ANGULAR INSERTION DEPTH[1]

Introduction

The performance benefit of *strict* place-based maps may not be experienced by recipients of short electrode arrays (e.g., ≤ 24 mm) since information below the frequency associated with the most apical electrode is discarded. Recipients of short electrode arrays may benefit from a *full-frequency* place-based map that aligns the critical speech information (e.g., 1 – 3 kHz; ANSI, 1997; Warren et al., 1995) and compresses lower and higher frequency information to provide more of the speech spectrum. The pattern of performance with the full-frequency place-based map may differ for CI versus EAS users due to acoustic hearing in the implanted ear serving as an anchor for cochlear tonotopicity. The present experiment compared the masked speech recognition of participants with normal hearing when listening to CI or EAS simulations with two types of place-based maps using the cochlear place frequencies observed for three different actual recipients of short electrode arrays.

CI simulation studies suggest that recipients of short electrode arrays can tolerate the loss of some low-frequency information with strict place-based maps, though there are limits at which performance deteriorates. Fu and Shannon (1999b) observed minimal changes in vowel recognition with CI simulations of strict place-based maps for insertion depths ranging from 28

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[1] This chapter has been submitted as an article in Trends in Hearing: Dillon, M.T., Buss, E., Johnson, A., Canfarotta, M.W., O'Connell, B.P. (submitted). Place-based mapping of low-frequency speech information for simulations of cochlear implant and electric-acoustic stimulation devices as a function of insertion depth. *Trends in Hearing*.

mm (lower filter frequency, LF = 289 Hz) to 21 mm (LF = 960 Hz). These data indicated that listeners could tolerate the loss of low-frequency information up to at least 960 Hz with strict place-based maps. Faulkner and colleagues (2003) assessed speech recognition using consonant, vowel, and sentence stimuli with CI simulations of strict place-based maps for insertion depths of 25 mm (center frequency, CF = 502 Hz) to 17 mm (CF = 1851 Hz). Speech recognition began to decline at the shallower insertion depths (i.e., ≤ 19 mm, CF = 1364 Hz), presumably due to the loss of low- to mid-frequency information. In 4 CI users, Başkent and Shannon (2005) simulated shallow insertion depths ranging from 28 mm to 7 mm by deactivating apical electrodes. For each simulated insertion depth, speech recognition was assessed with strict place-based maps and maps with compression applied to provide a wider input frequency range. For deeper insertion depths, CI users had better performance with the strict place-based maps compared to the compressed, spectrally shifted maps. Performance declined with the strict place-based maps as the simulated insertion depth decreased. At approximately 19 mm (CF: 1332 Hz), CI users began performing better with the compressed, spectrally shifted maps than the strict place-based maps. These findings demonstrate that strictly aligning the filter frequencies to cochlear tonotopicity may be detrimental for the speech recognition of recipients of short electrode arrays.

Recipients of short electrode arrays may benefit from maps that align a portion of the speech spectrum to cochlear place. Preliminary data suggest that listeners of place-based maps may tolerate the loss of some low-frequency information if the mid-frequency information (e.g., 1 – 3 kHz) is aligned with the cochlear place frequencies (Başkent & Shannon, 2007; Warren et al., 1995). Warren and colleagues (1995) evaluated recognition of sentences that were filtered into narrow bands, with stimulus CFs ranging from 370 to 6000 Hz. Participant performance was best when provided with mid-frequency information (i.e., CF = 1500 Hz) as compared to lower or higher frequency information. In a CI simulation study of 25- and 20-mm electrode arrays, Başkent and Shannon (2007) compared vowel and consonant recognition for 5 participants with normal hearing listening to strict place-based maps (carrier filters and analysis filters matched), spectrally shifted maps (carrier filters shifted higher or lower than the analysis bands), and spectrally shifted maps with compression (wider analysis bands). As expected, performance was best with the strict place-based maps than either the spectrally shifted maps or spectrally shifted maps with compression. For some of the simulated conditions, the spectrally shifted maps with compression had minimal electric frequency-to-place mismatches in the mid-frequency region (i.e., 1 – 2 kHz). Notably, performance was better with the spectrally shifted maps with compression when mismatches were minimal for the mid frequencies. No such benefit was observed when mismatches were minimal for the high frequencies (i.e., > 8 kHz). Taken together, these data suggest that recipients of short electrode arrays may benefit from place-based mapping procedures that prioritize the alignment of the critical mid-frequency information and inclusion of low-frequency information regardless of place.

Comparison of place-based mapping procedures

An alternative to our *strict* place-based mapping procedure is a *full-frequency* place-based mapping procedure that assigns the filter frequencies to align with the cochlear place frequencies for electrodes in the mid-frequency cochlear region and compresses lower and higher frequency information non-tonotopically across electrodes in the apical and basal regions. Thus, the difference between the strict and full-frequency place-based mapping procedures is the distribution of low-frequency information for electrodes below the 1 kHz cochlear region. Listeners may experience better speech recognition with full-frequency maps than with strict maps due to access to more low-frequency information. On the other hand, listeners may experience poorer speech recognition with full-frequency maps than with strict maps due to the spectral shifts of low-frequency information. The present experiment compared the masked speech recognition with full-frequency maps versus strict maps to determine whether presenting low-frequency information with intentional spectral shifts offers an advantage over discarding low-frequency information when the mid-frequency information is aligned with cochlear place for recipients of short electrode arrays.

Differences in speech recognition performance with strict maps versus full-frequency maps are likely influenced by the specific AID of the electrode array. For shallower insertion depths, more low-frequency information is discarded with strict maps, and larger spectral shifts of low-frequency information are presented with full-frequency maps. To support optimal performance for our clinical population, we need to understand the conditions under which full-frequency maps are preferrable to strict maps. The average AID of the most apical electrode for currently available short electrode arrays are 428º (SD: 34º) for the MED-EL Flex24 array (Canfarotta et al., 2020), 411º (SD: 78º) for the Cochlear CI422 Slim Straight array (O'Connell et al., 2016), and 393º (SD: 62º) for the Advanced Bionics SlimJ array (Lenarz et al., 2020). These AIDs equate to cochlear place frequencies of 590 Hz, 646 Hz, and 713 Hz, respectively, when using a spiral ganglion (SG) frequency-to-place function (Stakhovskaya et al., 2007). The present experiment simulated three cases of short 12-channel electrode arrays with AIDs that were within the range observed clinically for short arrays [460º (498 Hz), 389º (728 Hz), and 335º (987 Hz)].

Differences in performance with strict versus full-frequency maps could also vary based on access to acoustic low-frequency cues; that is, whether the listener has functional acoustic hearing and uses an EAS device or does not have functional acoustic hearing and uses a CI device. For CI users with short electrode arrays at shallows AIDs, we hypothesized that performance with the strict map (*CI-strict*) would decline with decreases in AID and the benefit of the full-frequency map (*CI-full*) would be observed, as described above. The prediction for EAS users is less clear. For EAS users, the acoustic hearing in the implanted ear would provide access to some low-frequency information and may serve as an anchor to cochlear tonotopicity. Thus, EAS users may experience better performance with strict maps (*EAS-strict*) than full-frequency maps (*EAS-full*) over a wider range of AIDs.

The present experiment evaluated the masked speech recognition of participants with normal hearing while listening with either a CI or EAS simulation with a strict versus full-frequency place-based map for cases of short electrode arrays. The aims were to assess whether a full-frequency place-based mapping procedure was preferrable over our strict place-based mapping procedure, review whether the patterns of performance with the two place-based maps differ as a function of simulated AID, and evaluate whether the addition of acoustic low-frequency cues influences performance differences with the two maps.

Methods

The study-site Biomedical Institutional Review Board (IRB) approved the assessment of masked speech recognition while listening to vocoded speech (IRB approval #86-0059). Listeners provided written consent and were compensated $15.00 per hour.

Participants

Sixty young adults (40 female) participated. Listeners were between 18 and 29 years of age, with a mean age of 23 years (SD: 3 years). Hearing sensitivity was assessed behaviorally in either a single-walled or double-walled sound booth. Listeners detected pure-tone stimuli at ≤ 25 dB HL for octave frequencies .125 to 8 kHz and for 12.5 kHz. Listeners were native speakers of American English with no previous listening experience to vocoded speech.

Stimuli

A 12-channel noise vocoder simulated the electric outputs for the CI and EAS simulations using a bank of bandpass finite impulse response (FIR) filters. Tap arrays were generated using the *fir1* function (MATLAB, 2019a). For each filter, the number of taps used to define the magnitude spectrum was selected such that spectral resolution was 20% of the filter bandwidth; synchronous output across filters was accomplished by symmetrically padding the arrays with zeros. The CFs for the bandpass filters were the CFs for each channel derived from either the strict or full-frequency place-based mapping procedure (listed in Table 1 and described below). The edge filter frequency for adjacent channels was the geometric mean of the CFs for the two channels. The low-frequency cutoff for the most apical electrode (E1) and the high-frequency cutoff for the most basal electrode (E12) were set such that each CF was the geometric mean of the upper and lower cutoff (listed in Table 1). The Hilbert envelope was extracted from the output of each filter, low-pass filtered at 300 Hz with a 4th order Butterworth filter, and used to amplitude modulate a corresponding noise band. The noise bands were filtered using the cochlear place frequencies for each case (listed in Table 1).

Table 1. The cochlear place frequency for each electrode (E; listed in bold) and center frequency of the associated channel using either the strict or full-frequency place-based mapping procedure for each simulated case of a 12-channel short electrode array.

E1 is the most apical electrode and E12 is the most basal electrode. Gray shading indicates the filter bandwidth did not include the simulated cochlear place frequency. The low-frequency filter (LF) for the vocoder is listed for the cochlear implant (CI) and electric-acoustic stimulation (EAS) simulations. For Case 1, E1 is within the region of functional acoustic hearing for the EAS simulations. An 11-channel vocoder (E2-E12) simulated the reduction of the stimulation level for E1 below detection to limit electric-on-acoustic masking; thus, the LF differs for the CI and EAS simulations for Case 1. Frequency is reported in Hertz.

		CI LF	EAS LF	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12
Case 1 (460º)	**cochlear place**			**498**	**674**	**855**	**1029**	**1303**	**1796**	**2594**	**3649**	**4930**	**6730**	**8902**	**11647**
	strict	428	602	498	674	844	1042	1331	1817	2577	3405	4173	5114	6266	7678
	full-frequency	102	206	142	276	496	872	1331	1817	2577	3405	4173	5114	6266	7678
Case 2 (389º)	**cochlear place**			**728**	**865**	**1060**	**1320**	**1796**	**2498**	**3590**	**5063**	**7261**	**9653**	**12441**	**14709**
	strict	665	665	728	872	1064	1349	1806	2518	3573	4568	5244	6020	6911	7933
	full-frequency	212	212	309	657	1064	1349	1806	2518	3573	4568	5244	6020	6911	7933
Case 3 (335º)	**cochlear place**			**987**	**1240**	**1623**	**2187**	**2912**	**3590**	**4716**	**6073**	**8314**	**10264**	**12441**	**14157**
	strict	876	876	987	1253	1635	2181	2856	3464	3977	4565	5241	6018	6910	7933
	full-frequency	591	591	759	1253	1635	2181	2856	3464	3977	4565	5241	6018	6910	7933

For the EAS simulations, acoustic low-frequency information was added to the noise vocoder. A FIR filter shaped the acoustic output to simulate aided sound field thresholds of 30, 30, 55, and 65 dB HL at .125, .25, .5, and 1 kHz, respectively. The rationale was to simulate the acoustic low-frequency information available to an EAS user with a moderate hearing loss at .125 and .25 kHz and a severe hearing loss at .5 and 1 kHz. The acoustic hearing was not incorporated into the electric filter assignments of the strict and full-frequency maps, as is with the current clinical default mapping procedures for EAS devices. For the present study, vocoder settings were consistent for the EAS and CI simulations to facilitate a direct performance comparison with and without acoustic low-frequency cues. This procedure avoided the differences in frequency-to-place mismatches for EAS and CI simulations that would have occurred if the acoustic hearing had been used to define the electric low-frequency filter for the EAS simulations. This procedure resulted in some overlap of the acoustic and electric input frequencies in the EAS-full condition for Case 1 and Case 2 (discussed below).

Simulated cases of short electrode arrays

Three cases of a 12-channel short electrode array were simulated by assigning the carrier frequency for an individual channel as the cochlear place frequency of the associated electrode (listed in Table 1). The AID and cochlear place frequency for the most apical electrode was 460º and 498 Hz for Case 1, 389º and 728 Hz for Case 2, and 335º and 987 Hz for Case 3, respectively. These example cases were selected because they are within the range of AIDs reported for recipients of short electrode arrays that are used clinically (Canfarotta et al., 2020; Landsberger et al., 2015; Lenarz et al., 2020; O'Connell et al., 2016).

For Case 1 (460º/498 Hz), the most apical electrode is within the region of functional acoustic hearing for the EAS simulation. Stimulation from electrodes within the region of functional acoustic hearing may interfere with the neural response to the acoustic signal, known as electric-on-acoustic masking (Imsiecke et al., 2020a; Kipping et al., 2020; Krüger et al., 2017; Lin et al., 2011; Stronks et al., 2010, 2012). Our place-based mapping procedures attempt to limit electric-on-acoustic masking by reducing the stimulation level below detection for electrodes within the region of functional acoustic hearing. For the present study, this was simulated for Case 1 by omitting the vocoder band associated with E1 for the EAS simulations. That is, an 11-channel vocoder (E2-E12) was used for the EAS-strict and EAS-full conditions.

Strict versus full-frequency place-based mapping procedures

The CFs for the bandpass filters were derived using either the strict or full-frequency place-based mapping procedure and are listed in Table 1. For both mapping procedures, the filter frequencies were adjusted to align the input with the cochlear place frequencies for electrodes residing within the mid-frequency cochlear region (i.e., 1 – 3 kHz). The rationale was to eliminate frequency-to-place mismatches within this critical speech frequency region. The high-frequency information was distributed across the remaining channels for electrodes in the basal cochlear region (i.e., > 3 kHz). Thus, filter frequencies for the strict and full-frequency maps were similar for electrodes in the mid- to high-frequency cochlear regions.

The strict and full-frequency mapping procedures differed in the distribution of low-frequency information. For the strict procedure, the filter frequencies were adjusted to align the input with the cochlear place frequencies for electrodes apical to the 1 kHz cochlear region. The rationale was to eliminate frequency-to-place mismatches for low- and mid-frequency speech information. Low-frequency information that was outside of the filter boundary for E1 was discarded. For the full-frequency procedure, the filters for the electrodes apical to the 1 kHz cochlear region were widened to provide more low-frequency information. Thus, strict maps aligned with cochlear tonotopicity yet discarded lower frequency information; full-frequency maps provided more of the speech spectrum yet spectrally shifted the low-frequency information.

Procedure

Participants completed a task of masked speech recognition while listening to either a CI or EAS simulation for one of the three cases. Listeners were seated in a quiet room. Stimuli were routed through an external sound card (M-AUDIO, M-Track 2x2) and presented diotically over headphones (Sennheiser, HD 280 Pro). The experiment was controlled by a custom MATLAB script.

Masked speech recognition was evaluated using an adaptive, ascending signal-to-noise ratio (SNR) procedure, as previously described by Buss et al. (2015) and used in our other vocoder experiments by Dillon et al. (2021a; 2022). Briefly, the AzBio sentences (Spahr et al., 2012) were presented in a 10-talker masker. The masker level was 60 dB SPL, and the starting level for the target was 0 dB SNR. The listener was asked to repeat the target and was scored for each word correctly repeated. Target level increased in 5 dB steps until the listener correctly repeated all the words in the sentence or the maximum SNR was reached (i.e., 20 dB). The ascending procedure was completed for each of the 20 sentences within the list. Feedback was not provided.

Twenty listeners provided data for each case (3 cases, 60 total listeners). For each case, four conditions were evaluated (i.e., CI-strict, CI-full, EAS-strict, and EAS-full). Listeners were randomized to listen with either CI or EAS simulations. For each device simulation, half of the participants listened with the strict map first, and half listened to the full-frequency map first to control for potential learning effects.

Data analysis

The proportion of correctly repeated words at each SNR was fitted with a three-parameter logit function (i.e., mean, slope, and asymptote) to generate the psychometric functions for the plots. For the data analysis, proportion correct values were restricted within 0.001-0.999, and a logit transformation was applied to normalize the variance (Oleson, Brown, & McCreery, 2019). A linear mixed model evaluated the main effects of sex, case (Cases 1, 2, and 3), condition (CI-full, CI-strict, EAS-full, and EAS-strict), and SNR (0, 5, 10, 15, and 20 dB), and the 2-way and 3-way interactions of case, condition, and SNR using the *lme* function in R statistical software (R Core Team, 2021), with a random intercept for each listener. Case and condition were entered as factors. Case 3 (335º/987 Hz) was the reference case due to the prediction that the performance benefit for strict over full-frequency maps would reverse for the case with the shallowest AID. SNR was mean centered on 10 dB.

Reduced models assessed the patterns of performance for the EAS and CI simulations individually to evaluate performance with strict versus full-frequency maps with and without acoustic low-frequency cues. The reduced models included main effects of case, map (strict and full-frequency), and SNR, as well as the associated interactions. Significance was defined as $\propto < 0.05$.

Results

Figure 1 shows psychometric functions fitted to the mean proportion correct. Data for the three cases are shown in separate panels. Mean proportion correct at each SNR is indicated with circles for the CI simulations and diamonds for the EAS simulations. Filled symbols and solid lines indicate performance and fit with the full-frequency maps; open symbols and dashed lines indicate performance and fit with the strict maps. Functions fitted to data of individual listeners are plotted in Figure 2.

Figure 1. Psychometric functions fitted to mean proportion correct data for each case. Symbols show mean proportion correct at each SNR and line indicate fits for condition (i.e., CI-full, CI-strict, EAS-full, EAS-strict), as specified in the legend. The angular insertion depth and cochlear place frequency of the most apical electrode is provided for each case.

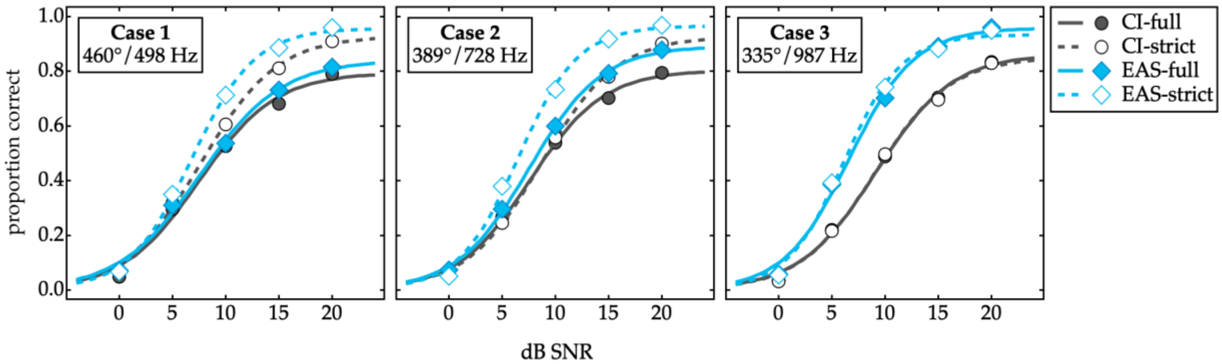


Figure 2. Psychometric functions fitted to the proportion correct data for individual listeners.

Listeners contributed data to Case 1 (top row), Case 2 (middle row), or Case 3 (bottom row). Results for the CI simulations are in gray (left two columns), and results for the EAS simulations are in blue (right two columns). Solid lines represent the data with the full-frequency place-based maps, and dashed lines represent the data with the strict place-based maps.

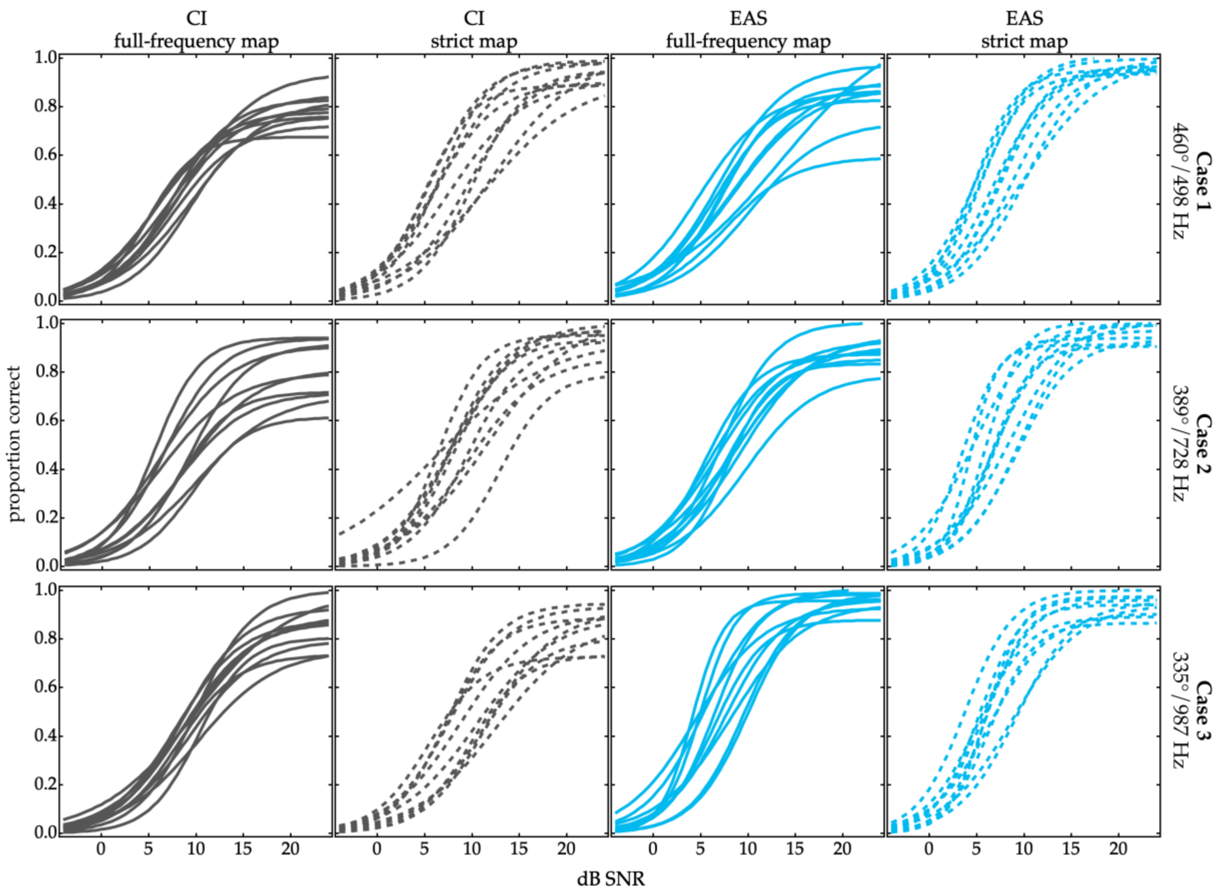


Table 2 lists the coefficients from the full model, which evaluated the main effects of sex, case, condition, and SNR, and the 2-way and 3-way interactions of case, condition, and SNR on masked speech recognition. There was a significant main effect of condition ($F_{(3,519)} = 5.87$, $p = 0.001$). As compared the CI-full condition, performance was significantly better with the EAS-full and EAS-strict conditions, likely due to the addition of the acoustic low-frequency cues (see below). The differences in performance between conditions were more pronounced at the higher SNRs (i.e., ≥ 10 dB), with a significant interaction between condition and SNR ($F_{(3,519)} = 6.40$, $p < 0.001$). Also, there was a significant interaction between case and condition ($F_{(6,519)} = 4.01$, $p = 0.001$), indicating that the patterns of performance across the conditions differed for the three cases. In contrast to the other conditions, performance for the EAS-strict and CI-full conditions were relatively consistent across cases. For example, at 10 dB SNR the proportion correct as AID decreased (Case 1 to Case 3) was 0.71, 0.73, and 0.74 for EAS-strict and 0.53, 0.54, and 0.49 for CI-full. For the EAS-full condition, performance improved as the AID decreased (i.e., 0.54, 0.60, and 0.70, respectively at 10 dB SNR). Conversely, performance declined as the AID decreased for the CI-strict condition (i.e., 0.61, 0.56, and 0.50, respectively at 10 dB SNR). There was a significant 3-way interaction ($F_{(6,519)} = 3.99$, $p = 0.001$) between case, condition, and SNR, indicating that the case-by-condition interaction was most pronounced at high SNRs. There was no significant main effect of sex ($F_{(1,56)} = 0.78$, $p = 0.381$); this variable was removed from subsequent models.

Table 2. Regression coefficients from the full LMM that evaluated the main effects of sex, case, condition, and SNR, and the 2-way and 3-way interactions of case, condition, and SNR.

Significant results are indicated in bold and italic. Case 3 (335º/987 Hz) was the reference case. The default for condition was CI-full. SNR was mean centered on 10 dB.

	Coefficient	SE	DF	t-value	p-value
Sex	-0.18	.20	56	-0.88	0.381
Case (Case 1)	0.22	0.33	56	0.66	0.514
Case (Case 2)	0.19	0.34	56	0.57	0.570
Condition (CI-strict)	-0.03	0.19	519	-0.15	0.877
Condition (EAS-full)	***1.26***	***0.33***	***519***	***3.83***	***<0.001***
Condition (EAS-strict)	***1.23***	***0.33***	***519***	***3.74***	***<0.001***
SNR	***0.27***	***0.02***	***519***	***14.46***	***<0.001***
Case 1: CI-strict	***0.64***	***0.27***	***519***	***2.40***	***0.017***
Case 2: CI-strict	0.30	0.27	519	1.10	0.271
Case 1: EAS-full	***-1.08***	***0.46***	***519***	***-2.33***	***0.020***
Case 2: EAS-full	-0.74	0.46	519	-1.58	0.114
Case 1: EAS-strict	-0.21	0.46	519	-0.44	0.658
Case 2: EAS-strict	0.06	0.46	519	0.12	0.902
Case 1: SNR	***-0.05***	***0.03***	***519***	***-2.01***	***0.045***
Case 2: SNR	-0.02	0.03	519	-0.78	0.435
CI-strict: SNR	0.00	0.03	519	0.14	0.886
EAS-full: SNR	***0.09***	***0.03***	***519***	***3.45***	***<0.001***
EAS-strict: SNR	***0.08***	***0.03***	***519***	***2.82***	***0.005***
Case 1: CI-strict: SNR	0.04	0.04	519	1.03	0.304
Case 2: CI-strict: SNR	0.04	0.04	519	1.09	0.276
Case 1: EAS-full: SNR	***-0.09***	***0.04***	***519***	***-2.38***	***0.018***
Case 2: EAS-full: SNR	***-0.10***	***0.04***	***519***	***-2.65***	***0.008***
Case 1: EAS-strict: SNR	0.04	0.04	519	1.02	0.306
Case 2: EAS-strict: SNR	0.05	0.04	519	1.35	0.177

To further evaluate the interaction between case and condition, reduced models evaluated the EAS and CI simulation data separately to assess performance between the strict and full-frequency maps with and without acoustic low-frequency cues. Table 3 lists the coefficients for the model that assessed the data from the CI-strict and CI-full conditions. The main effects of case and map were non-significant ($p \geq 0.172$). There was a significant interaction between case and map ($F_{(2,261)} = 6.19$, $p = 0.002$), indicating differences in the patterns of performance with the strict versus full-frequency maps across the cases. Review of the fixed effects demonstrate that listeners experienced significantly better performance with the strict map for Cases 1 and 2 ($p \leq 0.004$); the non-significant effect of map indicates that this benefit was not observed for Case 3. Taken together, these data indicate that our strict place-based mapping procedure may not be detrimental for the performance for CI users with short electrode arrays at AIDs of ≥ 335º. Additionally, there was a significant 3-way interaction between case, map, and SNR ($F_{(2,261)} = 8.82$, $p < 0.001$), indicating that the interaction between effects of map and case was largest at high SNRs.

Table 3. Regression coefficients from the reduced LMM for the CI simulations that evaluated the main effects of case, map, and SNR, and their 2-way and 3-way interactions.

Significant results are indicated in bold and italic. Case 3 (335º/987 Hz) was the reference case. The default for map was the full-frequency map. SNR was mean centered on 10 dB.

	Coefficient	SE	DF	t-value	p-value
Case (Case 1)	0.86	0.54	27	1.58	0.125
Case (Case 2)	0.95	0.54	27	1.76	0.089
Map	0.03	0.19	261	0.15	0.880
SNR	***0.33***	***0.04***	***261***	***7.64***	***<0.001***
Case 1: Map	***-0.88***	***0.28***	***261***	***-3.19***	***0.002***
Case 2: Map	***-0.79***	***0.28***	***261***	***-2.88***	***0.004***
Case 1: SNR	0.11	0.06	261	1.85	0.065
Case 2: SNR	***0.18***	***0.06***	***261***	***2.95***	***0.003***
Map: SNR	0.02	0.03	261	0.62	0.537
Case 1: Map: SNR	***-0.13***	***0.04***	***261***	***-3.31***	***0.001***
Case 2: Map: SNR	***-0.15***	***0.04***	***261***	***-3.89***	***<0.001***

For the EAS simulations, we predicted better performance with strict maps than full-frequency maps over a wider range of AIDs due to the acoustic low-frequency information serving as an anchor to cochlear tonotopicity. Table 4 lists the coefficients for the model that assessed the data from the EAS simulations. There was a significant main effect of case ($F_{(2,27)}$ = 5.06, p = 0.014), with fixed effects demonstrating a significant difference in performance between Cases 1 and 3 (p = 0.004), but not for Cases 2 and 3 (p = 0.131). There was a significant interaction between case and map ($F_{(2,261)}$ = 3.07, p = 0.048), with fixed effects demonstrating different patterns of results for the two maps for Case 1 as compared to Case 3 (p = 0.014) but not for Case 2 as compared to Case 3 (p = 0.258). These data reflect the fact that listeners experienced an improvement with the full-frequency maps as AID decreased, which was similar to the performance observed with the strict maps for the shallower cases (i.e., Cases 2 and 3). These results suggest that EAS users with functional acoustic hearing at .125 and .25 kHz and an electrode array placed within 389 - 335º may experience similar performance with strict and full-frequency maps. Better performance with a strict map may be experienced for electrode arrays at deeper AIDs (e.g., 460º).

Table 4. Regression coefficients from the LMM for the EAS simulations that evaluated the main effects of case, map, and SNR, and their 2-way and 3-way interactions.

Significant results are indicated in bold and italic. Case 3 (335º/987 Hz) was the reference case. The default for map was the full-frequency map. SNR was mean centered on 10 dB.

	Coefficient	SE	DF	t-value	p-value
Case (Case 1)	***1.45***	***0.46***	***27***	***3.18***	***0.004***
Case (Case 2)	0.71	0.46	27	1.56	0.131
Map	0.03	0.18	261	0.16	0.874
SNR	***0.28***	***0.04***	***261***	***6.85***	***<0.001***
Case 1: Map	***-0.64***	***0.26***	***261***	***-2.48***	***0.014***
Case 2: Map	-0.30	0.26	261	-1.13	0.258
Case 1: SNR	0.02	0.06	261	0.41	0.680
Case 2: SNR	0.06	0.06	261	1.06	0.289
Map: SNR	-0.00	0.03	261	-0.15	0.883
Case 1: Map: SNR	-0.04	0.04	261	-1.06	0.290
Case 2: Map: SNR	-0.04	0.04	261	-1.12	0.262

Discussion

There is a growing interest in individualizing the mapping of electric stimulation for CI and EAS users, such as with place-based mapping; however, the optimal procedure remains unclear. Our strict place-based mapping procedure aligns the electric filter frequencies to the cochlear place frequencies up to at least 3 kHz and distributes the remaining high frequency information across the basal electrodes. The effectiveness of strictly aligning the electric filters to cochlear tonotopicity may be limited for recipients of short electrode arrays due to the loss of low-frequency information (Başkent & Shannon, 2005; Faulkner et al., 2003; Fu & Shannon, 1999b). An alternative to our strict place-based mapping procedure is a full-frequency place-based mapping procedure that aligns the critical speech information (e.g., 1 – 3 kHz) and compresses lower and higher frequency information to provide more of the speech spectrum. The present experiment compared the masked speech recognition for CI and EAS simulations with strict versus full-frequency maps for three cases of short electrode arrays. Generally, listeners experienced better performance with strict maps than full-frequency maps for Case 1 (460º/498 Hz) and Case 2 (389º/728 Hz). For Case 3 (335º/987 Hz), listeners experienced similar performance with strict maps and full-frequency maps. This is not entirely surprising since the two maps only differed in the frequency information provided by E1. These data support the conclusion that our strict place-based maps offer similar or better acute performance than full-frequency place-based maps for recipients of the short electrode arrays used by our center.

The effects of listening with a strict map or a full-frequency map differed for the CI and EAS simulations. For the CI simulations, performance with the strict maps declined with decreases in AID, while the performance with the full-frequency maps was relatively consistent across the three cases. The observation of degraded performance with the strict maps as AID decreased corroborates previous CI simulations demonstrating declines in speech recognition in quiet at shallow insertion depths due to the loss of low-frequency information (Başkent & Shannon, 2005; Faulkner et al., 2003; Fu & Shannon, 1999b). Interestingly, performance in the present study was relatively consistent with the full-frequency maps across cases – despite differences in the number of low-frequency channels with spectral shifts. Case 1 had more channels with spectral shifts (n=3) than Case 2 (n=2) or Case 3 (n=1). Additionally, the present data suggest that our strict place-based mapping procedure is preferrable for AIDs $\geq 389^{o}$; similar performance may be experienced with strict and full-frequency maps at shallower AIDs that are within the range observed clinically for short electrode arrays.

In contrast to CI simulations, results from the EAS simulations indicate that performance with the strict maps was relatively consistent across the three cases despite differences in the available electric frequency information. Whereas performance in the CI-strict condition declined with decreases in AID, consistent performance in the EAS-strict condition across cases is likely due to the inclusion of low-frequency acoustic cues. These data corroborate previous EAS simulation data that demonstrate superior performance with strict place-based maps over spectrally shifted maps – even when there is a frequency information gap between the acoustic and electric outputs (Dillon et al., 2021a; Fu et al., 2017; Willis et al., 2020). Current default mapping procedures for EAS devices use the unaided hearing thresholds in the implanted ear to determine the electric filter settings, which creates spectral shifts of ½ octave or more for the majority of EAS users (Canfarotta et al., 2020). The present data combined with previous EAS simulation data suggest that incorporating the individual differences in the placement of the electrode array relative to cochlear tonotopicity into the mapping of EAS devices may support better performance than with current default procedures, although is it unclear whether this benefit would be observed with additional listening experience.

Another finding from the EAS simulations was the emerging benefit with the full-frequency maps as AID decreased. This performance benefit may have been due to decreases in the number of channels with spectrally shifted low-frequency information. However, this possibility seems unlikely since Cases 1 and 2 had two channels with spectral shifts and Case 3 had one channel. As a reminder, the EAS simulations for Case 1 used an 11-channel vocoder to simulate the lowered stimulation of E1 to limit electric-on-acoustic masking. It seems more likely that the increasing benefit of the full-frequency map with decreases in AID was due to the inclusion of some spectrally shifted low-frequency information that was not redundant with the acoustic information. The present data cannot differentiate effects of spectrally shifting low-frequency electric information versus the redundancy of acoustic and electric information on the performance with the EAS-full condition for Cases 1 and 2. Notably, performance with the full-frequency map did not exceed that with the strict map for the case with the shallowest insertion depth. Taken together, strict place-based maps may support better performance for EAS users than full-frequency place-based maps – at least using the AIDs, settings, and acoustic hearing simulated in the present study.

The present data suggest the utility of our strict place-based mapping procedure as compared to a full-frequency place-based mapping procedure, though there are limitations worth consideration. The present study assessed the acute performance for listeners with normal hearing who did not have previous experience with vocoded speech. CI and EAS users may acclimate to spectral shifts with prolonged listening experience and/or auditory training (Faulkner, 2006; Fu et al., 2002, 2005; Fu & Galvin, 2003; Li & Fu, 2007; Li et al., 2009; Reiss et al., 2007, 2014; Rosen et al., 1999; Sagi et al., 2010; Smalt et al., 2013; Svirsky et al., 2004, 2015b; Vermeire et al., 2015). As such, the acute performance differences observed in the present study may not represent the long-term performance of CI and EAS users. On the other hand, acclimatization to spectrally shifted maps does not always overcome performance deficits (Reiss et al., 2007, 2014; Sagi et al., 2010; Svirsky et al., 2015b), and there are individual differences in the ability to acclimate to spectrally shifted maps (Smith & Winn, 2021). Additionally, performance differences between strict and full-frequency maps may be reduced in CI and EAS users due to current spread and channel interactions (Friesen et al., 2001; Fu & Shannon, 1999a). Finally, we cannot rule out the potential influence of high-frequency spectral shifts on the observed patterns of performance. There was an increase in the number of channels with spectrally shifted high-frequency information as the AID decreased. These shifts may have contributed to the decline in performance in the CI-strict condition as AID decreased. Investigation is needed to determine performance differences between the present place-based mapping procedure and procedures that strictly align all frequency information to cochlear tonotopicity, such as deactivating electrodes that exceed the current upper filter frequency limits (e.g., 8.5 kHz).

Conclusions

The present CI and EAS simulation data provide preliminary support for the use of a strict place-based mapping procedure for CI and EAS users with AIDs ≥ 389º. In Experiment 2, we evaluated the influence of electric frequency-to-place mismatches on the early speech recognition of EAS users listening with a strict place-based map or a default map.

CHAPTER 3: INFLUENCE OF ELECTRIC FREQUENCY-TO-PLACE MISMATCHES ON THE EARLY SPEECH RECOGNITION OUTCOMES FOR ELECTRIC-ACOUSTIC STIMULATION (EAS)[2]

Introduction

The experiment from Chapter 2 and our previous EAS simulation studies (Dillon et al., 2021a, 2022) found better speech recognition for strict place-based maps as compared to default maps or full-frequency place-based maps for participants with normal hearing listening to EAS simulations. It remained unclear whether the performance differences with simulated strict place-based maps versus default maps for EAS simulations (Dillon et al., 2021a, 2022; Fu et al., 2017; Willis et al., 2020) would also be observed for actual EAS users. The present chapter assessed the influence of electric frequency-to-place mismatches on the early speech recognition outcomes of EAS users. The study sample included EAS users who listened exclusively to either default maps (variable magnitudes of electric mismatch across individuals) or place-based maps (no electric mismatch). The hypotheses were that early speech recognition outcomes are better for EAS users with smaller electric mismatches, and that the negative influence of larger electric mismatches persist over the initial months of EAS listening experience.

Methods

Preliminary data were reviewed from an ongoing, prospective investigation of performance with default versus place-based maps for CI recipients. The study site Institutional

[2] This chapter has been submitted as an article in American Journal of Audiology: Dillon, M., Canfarotta, M., Buss, E., Rooth, M., Richter, M., Overton, A., Roth, N., Dillon, S., Raymond, J., Young, A., Pearson, A., Davis, A., Dedmon, M., Brown, K., O'Connell, B. (submitted). Influence of electric frequency-to-place mismatches on the early speech recognition outcomes for electric-acoustic stimulation (EAS) users. *American Journal of Audiology*.

Review Board approved the procedures, and participants provided consent. Participants were randomized to listen exclusively with either a default or place-based map. Procedures were completed at device activation (2-4 weeks post-operatively), and at 1-, 3-, and 6-months post-activation. Both the research audiologist who completed the assessments and the participants were blinded to the assigned map.

Participants

Adult CI recipients were considered for inclusion if they underwent cochlear implantation at the study site, received a MED-EL lateral wall electrode array (Innsbruck, Austria), were 18-80 years of age at the time of surgery, and presented with an unaided hearing threshold of ≤ 65 dB HL at 125 Hz in the implanted ear at device activation. Potential participants who failed the Mini Mental State Examination (Folstein, Folstein, & McHugh, 1975) or reported cognitive deficits were excluded.

Procedures

Unaided detection thresholds in the implanted ear were measured behaviorally using pure tone stimuli presented over insert earphones at each interval. A low-frequency pure tone average (LFPTA) was calculated from the unaided detection thresholds at 125, 250, and 500 Hz.

Participants were fit with the ear-level Sonnet2^{EAS} processor. The acoustic component was fit based on the participant's unaided detection thresholds in the implanted ear. The thresholds were entered into the clinical programming software (Maestro version 9), which determined the acoustic cutoff frequency by identifying the frequency at which the detection threshold exceeded 65 dB HL. The acoustic settings were verified using the NAL-NL1 prescriptive targets (Byrne et al., 2001), using either real-ear or test box measures with the Verifit2 hearing instrument analyzer (Audioscan). A value of 120 dB HL was entered to indicate no response at the output limit of the audiometer. For the CI component, the maximum comfortable loudness (MCL) levels were measured behaviorally for each channel using the "adjacent-reference method" (Throckmorton & Collins, 2001; Zwolan, Collins, & Wakefield, 1997). The threshold (T) levels for the map were 10% of the MCL for each channel at initial activation; at the post-activation intervals, behavioral thresholds were measured, and the T levels were set just below detection thresholds.

For participants randomized to listen with a default map, the electric filter frequencies were generated by the clinical software. The software assigned the low-frequency filter associated with the most apical electrode as the frequency where the unaided detection threshold exceeded 65 dB HL (the acoustic cutoff frequency). The remaining mid to high-frequency information was logarithmically distributed across the active channels.

For participants who were randomized to listen with a place-based map, the electric filter frequencies were assigned to align low to mid-frequency information with the cochlear place frequencies. Post-operative CT imaging was obtained for all cases using a Morita cone-beam CT scanner, and the image was uploaded to the OTOPLAN software (CAScination AG and MED-EL Corporation). Two reviewers manually identified cochlear anatomical landmarks (e.g., modiolus and round window) and individual electrodes for each CT image; those landmarks were used by the software to estimate the AID for each electrode, as previously described (Canfarotta et al., 2019). The cochlear place frequency for individual electrodes was calculated using a SG frequency-to-place function (Stakhovskaya et al., 2007). The SG function was selected based on a pilot study showing better acute speech recognition with place-based maps using the SG function as compared to an organ of Corti function (Dillon et al., 2021b). The filter frequencies were assigned to match the place frequency for electrodes residing up to at least the

3 kHz cochlear region. The remaining high-frequency information was logarithmically distributed across the more basal electrodes. For electrodes at cochlear place frequencies in the region of functional acoustic hearing (i.e., unaided detection threshold ≤ 65 dB HL), the MCL level was set below the participant's detection threshold (e.g., at 1 cu). For example, if a participant had an unaided threshold of 65 dB HL at 500 Hz, the stimulation level for an electrode at a cochlear place frequency < 500 Hz would be reduced. The rationale for this procedure was that it may limit potential electric-on-acoustic masking.

Speech recognition was assessed using tasks of vowel and word recognition. The assessment of vowel recognition was completed in a quiet room with a direct connect set-up. The participant's processor was connected to the computer using a 90/10 direct audio input cable. Twelve vowel sounds were presented in an /h/-vowel-/d/ context using the English Vowel Recognition Test from TigerSpeech Technology©. Participants listened to the target and selected the perceived vowel from a closed-set list. The assessment of word recognition was completed in a double-walled sound booth, with the participant seated one meter from the loudspeaker. Performance was assessed with CNC words (Peterson & Lehiste, 1962). The recorded 50-word lists were presented at 60 dB SPL, and the contralateral ear was masked. The tester scored each verbal response as correct or incorrect. For both tasks, performance was scored as the percent correct. The tasks were completed after mapping at the activation interval and prior to mapping at the post-activation intervals.

Electric frequency-to-place mismatch

Electric frequency-to-place mismatch was quantified as the semitone deviation between the electric center frequency and the SG place frequency for the electrode closest to the 1500 Hz cochlear place (~267°). The 1500 Hz place frequency was selected because it has been shown to be an important region for frequency alignment in CI simulations evaluating speech recognition (Başkent & Shannon, 2007).

Data analysis

Linear Mixed Models (LMM) implemented in R using the *lme* package (R Core Team, 2020) assessed the main effects of electric mismatch at 1500 Hz, interval, AID of E1, and the interaction of electric mismatch and interval on speech recognition, with participant included as a random factor. Percent correct data were converted to rationalized arcsine units to normalize the variance (Studebaker, 1985). In the statistical models, electric mismatch was converted to an absolute value, removing the distinction between basal and apical shifts.

Results

The data to date included 21 participants (11 female) who were randomized to listen with either a default map (n=15) or a place-based map (n = 6). Age at implantation ranged from 22 to 78 years, with a median of 66 years. Eleven participants were implanted with a Flex24 array, 6 with a Flex28 array, and 4 with a FlexSOFT array. All cases had a full insertion of the electrode array. The median AID of E1 was 503º, with a range of 370º to 691º. For participants with default maps, electric mismatch at 1500 Hz ranged from 2 to -12.0 semitones (median: -5 semitones)[3], with positive values indicating an apical shift and negative values indicating a basal shift of the spectral information relative to the cochlear place frequency. At the time of data review, there were more participants randomized to default maps than place-based maps, which provided a sufficient spread of electric mismatches to assess the influence on early performance. For participants with place-based maps, two participants (PB1 and PB3) had spectral gaps, and four participants (PB2, PB4, PB5, and PB6) had at least one electrode with stimulation levels

[3] 12 semitones equal one octave. In the statistical models, electric mismatch was converted to an absolute value, removing the distinction between basal and apical shifts.

reduced below threshold. Table 5 lists the demographic information for the sample; participants are ordered by AID of E1. Figure 3 plots the unaided detection thresholds for each participant at the initial activation and at the three post-activation intervals. Symbol shape and fill indicate the thresholds for each participant, as defined in Table 5.

Table 5. Demographic information for EAS users listening with either a default or a place-based map.

Participants are ordered by the angular insertion depth (AID) of the most apical electrode (E1). Symbol fill indicates whether the participant listened with a default (filled) or a place-based (open) map.

Participant/ Symbol	Sex	Age (yrs)	Electrode Array	AID of E1		Acoustic Cutoff (Hz)	Electrode at 1500 Hz	Electric Mismatch (semitone deviation)	Reduced Channel(s)
				degrees	Hz				
D1 ■	M	66	Flex24	370	809	542	4	-5	
D2 ▼	F	74	Flex24	404	671	300	4	-11	
D3 ◣	M	78	Flex24	410	650	250	4	-12	
PB1 ◇	F	45	Flex24	423	606	500	5	0	
PB2 ○	M	50	Flex24	428	590	625	5	0	E1
D4 ⧓	M	78	Flex24	429	587	286	5	-9	
D5 ◆	F	69	Flex24	452	520	219	5	-11	
D6 ▲	F	66	Flex24	483	442	187	5	-8	
D7 ⧫	F	52	Flex24	487	433	500	5	-1	
D8 ●	F	54	Flex24	495	415	203	5	-8	
D9 ◀	F	53	Flex24	503	398	563	5	2	
D10 ◤	F	73	Flex28	504	396	350	5	-3	
PB3 ⋈	M	73	Flex28	530	345	175	6	0	
D11 ⧗	M	67	Flex28	533	339	125	6	-5	
D12 ⬥	F	57	Flex28	542	323	208	6	-5	
D13 ◢	M	69	Flex28	545	318	250	6	-5	
PB4 □	M	52	FlexSOFT	575	269	214	6	0	E1
D14 ◥	M	69	Flex28	616	211	250	6	-2	
PB5 ▽	M	54	FlexSOFT	669	144	250	7	0	E1, E2
D15 ▶	F	22	FlexSOFT	689	120	125	6	-1	
PB6 △	F	67	FlexSOFT	691	118	125	6	0	E1

Age: Age at implantation

Figure 3. Unaided air-conduction pure-tone detection thresholds for each participant at initial activation and 1-, 3-, and 6-months post-activation.

Individual thresholds are indicated by symbol shape and fill, as defined in Table 5.

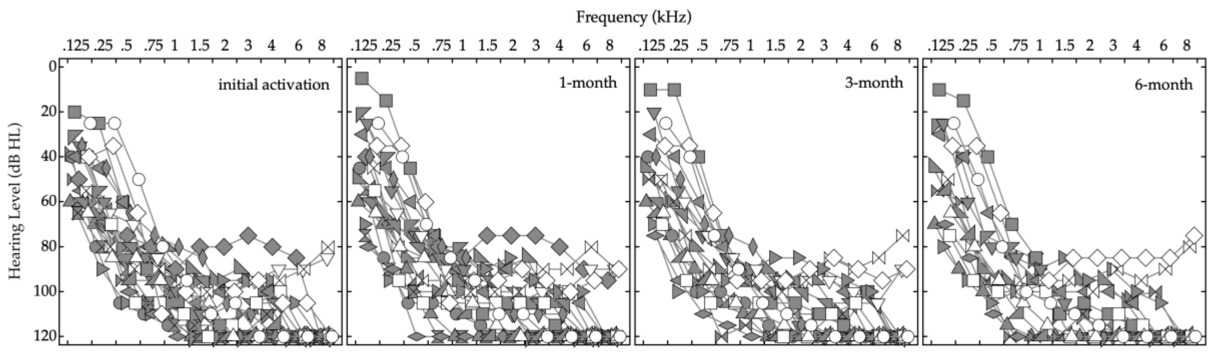


Figure 4 plots the speech recognition over time on the vowel recognition task (left column) and CNC words test (right column) as a function of electric mismatch at 1500 Hz. The LMMs included data from the post-activation intervals (1, 3, and 6 months); data from the initial activation were not included due to floor performance for some participants. Table 6 lists the coefficients for both LMMs. There was a significant main effect of electric mismatch for vowel recognition ($F_{(1,26)} = 5.5$, $p = 0.027$) and for CNC word recognition ($F_{(1,27)} = 4.6$, $p = 0.041$), with poorer performance observed for participants with larger magnitudes of electric mismatch on both tasks. The interaction of electric mismatch and interval was not significant for vowel recognition ($F_{(2,26)} = 0.59$, $p = 0.561$) or for CNC word recognition ($F_{(2,27)} = 1.4$, $p = 0.252$). These results indicate that EAS users with smaller magnitudes or no electric mismatch had better speech recognition scores than EAS users with larger magnitudes of electric mismatch over the first 6 months of listening experience.

Figure 4: Speech recognition as a function of electric frequency-to-place mismatch at 1500 Hz at initial activation and 1-, 3-, and 6-month post-activation.

Performance was assessed for vowel recognition (left column) and CNC words recognition (right column), scored as the percent correct. Individual performance is indicated by symbol shape and fill, as defined in Table 5. The vertical dashed line at 0 semitones indicates the alignment between the channel center frequency and the cochlear place frequency for the electrode closest to 1500 Hz.

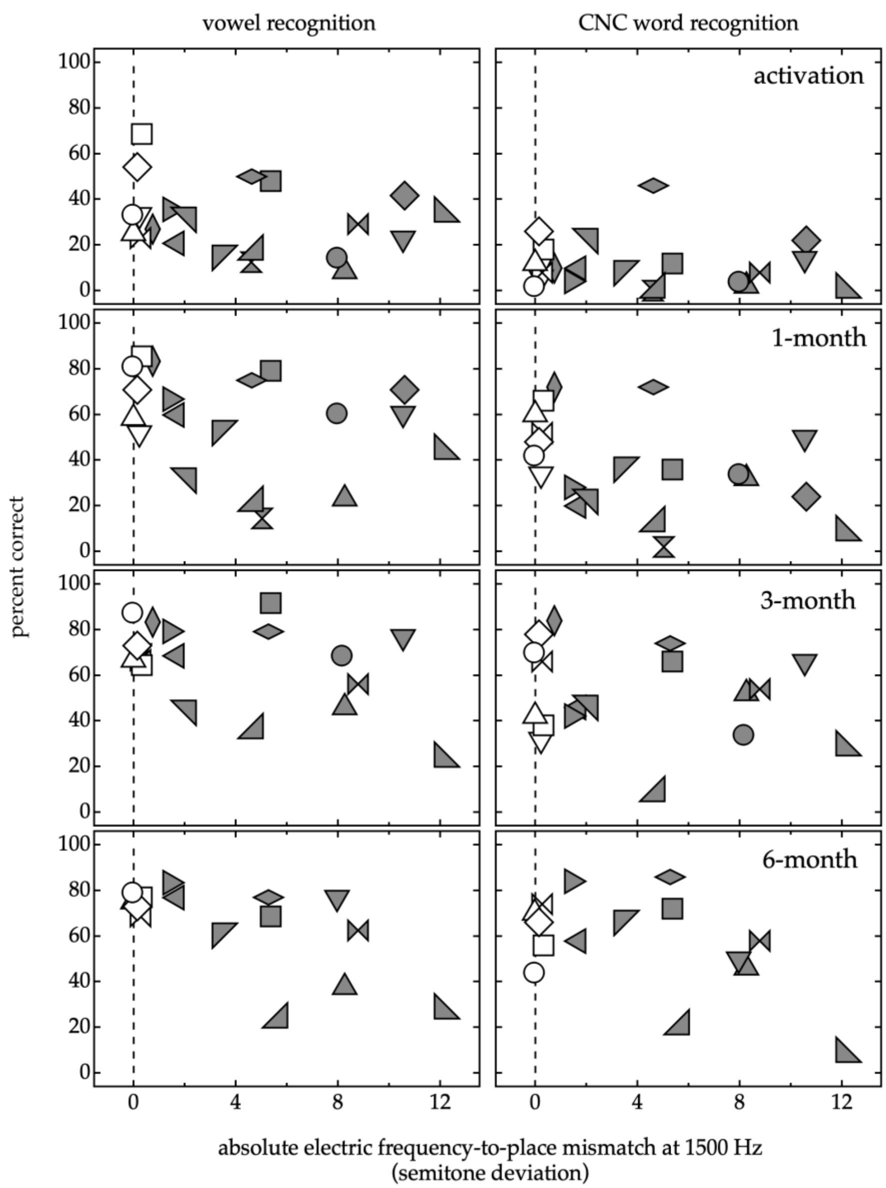


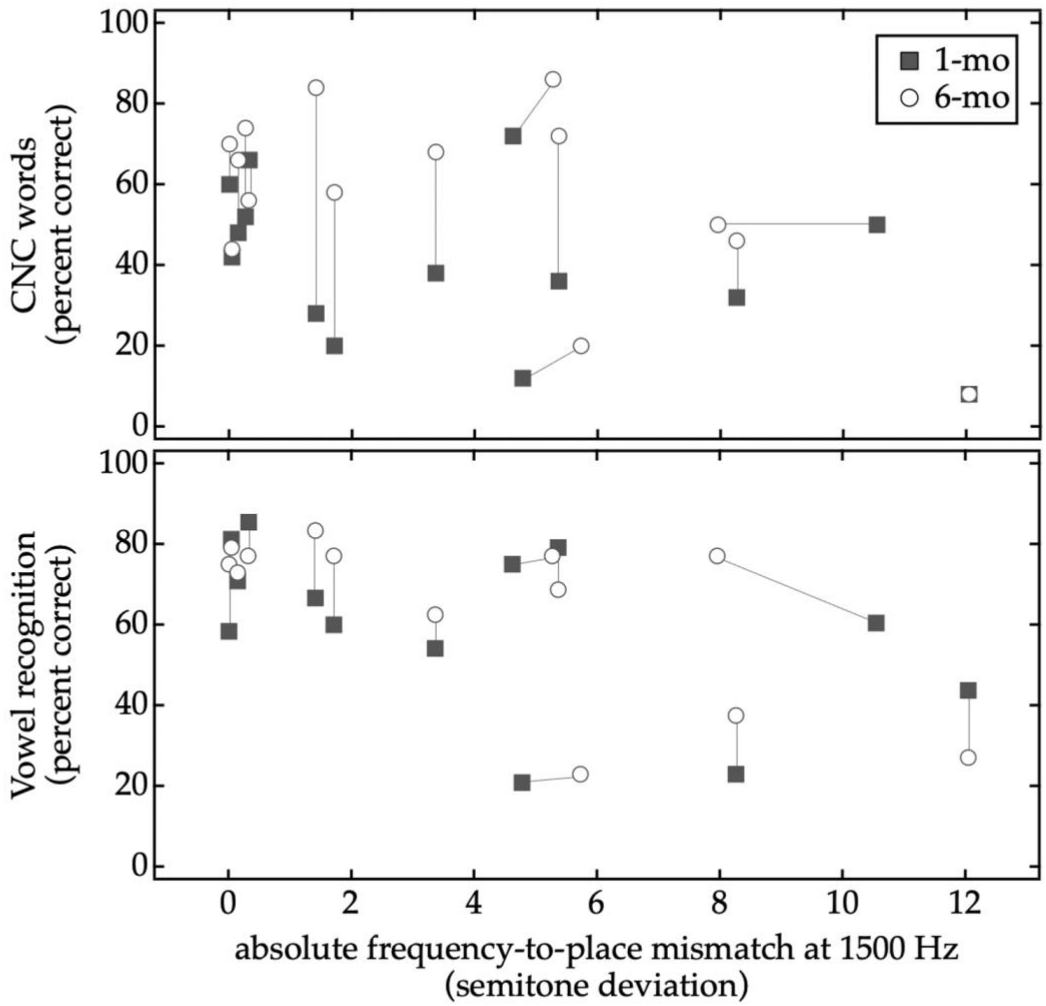
Table 6: Regression coefficients from the models that evaluated the main effects of interval (1, 3, and 6 months), absolute electric frequency-to-place mismatch at 1500 Hz, AID of E1, and the interaction of interval and electric mismatch.

Significant results are indicated in bold and italic. The 1-month post-activation visit was the reference for interval.

	Vowel Recognition					CNC Words Recognition				
	Coefficient	SE	DF	t-value	p-value	Coefficient	SE	DF	t-value	p-value
3 months	7.53	4.02	26	1.87	0.072	8.84	5.83	27	1.52	0.141
6 months	8.59	4.45	26	1.93	0.065	***21.76***	***6.43***	***27***	***3.39***	***0.002***
Electric mismatch	***-2.69***	***1.15***	***26***	***-2.34***	***0.027***	***-2.72***	***1.27***	***27***	***-2.14***	***0.041***
AID	-0.08	0.05	19	-1.74	0.098	-0.06	0.05	19	-1.29	0.213
3 months x Electric mismatch	-0.15	0.73	26	-0.21	0.837	0.91	1.07	27	0.85	0.403
6 months x Electric mismatch	-0.83	0.81	26	-1.03	0.314	-1.06	1.19	27	-0.89	0.379

Figure 5 plots the individual speech recognition data at the 1-month and 6-month intervals with lines indicating the change in performance between intervals as a function of electric mismatch at 1500 Hz. Trends observed in Figure 5 include that EAS users with no electric mismatches experienced an early increase in speech recognition that was relatively stable between the 1- and 6-month intervals, and EAS users of default maps with minimal electric mismatches experienced larger improvements in speech recognition between the 1- and 6-month intervals than EAS users of default maps with larger magnitudes of electric mismatches.

Figure 5: Individual speech recognition data at the 1-month and 6-month intervals. Percent correct scores for CNC words (top panel) and vowel recognition (bottom panel) are plotted as a function of absolute electric mismatch at 1500 Hz. Lines connect the individual data at the 1-month (filled squares) and 6-month (open circles) to depict the change in performance between the two intervals.



Additional analyses were conducted to evaluate other factors thought to affect performance in EAS users (i.e., LFPTA and age). No significant main effects were observed when the models were expanded to include LFPTA ($p \geq 0.259$); age at implantation was not significant for CNC words ($p = 0.510$) and trended towards significance for vowel recognition ($p = 0.056$).

Discussion

The present report prospectively evaluated the early speech recognition for EAS users as a function of electric mismatch. Participants listened exclusively to either default maps (median electric mismatch: -5 semitones) or place-based maps that eliminated electric mismatches for low to mid frequency information. Poorer early speech recognition was observed for EAS users with larger magnitudes of electric mismatches. For example, the model predicts poorer performance at 6-months post-activation for individuals listening to maps with 6 semitones of electric mismatch as compared to maps with no electric mismatch by 21 and 22 RAU for vowel and word recognition, respectively. There was no evidence of acclimatization to larger magnitudes of electric mismatches out to 6 months of EAS listening experience. These findings suggest the utility of methods to minimize or eliminate electric mismatches for EAS users, such as with a place-based mapping procedure, to support early speech recognition.

The early effects of electric frequency-to-place mismatches for EAS users corroborate the previously observed performance differences for participants with normal hearing listening to EAS simulations. In both paradigms, we observe better performance with place-based maps than for spectrally-shifted maps (Dillon et al., 2021a, 2022; Fu et al., 2017; Willis et al., 2020). For instance, Fu and colleagues (2017) observed better performance with simulations of a place-based map and a spectrally shifted map with minimal mismatches as compared to spectrally shifted maps with larger magnitudes of mismatch. In the present experiment, EAS users experienced better performance when electric mismatches were small, either with default maps that created minimal spectral shifts or with place-based maps. These findings are compelling considering the limited range of electric mismatches in the present dataset (2 to -12 semitones). EAS users with similar low-frequency acoustic hearing and who received shorter arrays (i.e., <24 mm), or a partial insertion with comparable length arrays, could experience even larger electric mismatches when listening with default maps.

One factor to consider when evaluating the present place-based mapping procedure is that it may result in a spectral gap between the acoustic and electric outputs. Default mapping procedures limit spectral gaps by assigning a single frequency to the acoustic cutoff and electric low-frequency filter. The poorer performance with spectral gaps for EAS users and listeners for EAS simulations (Dorman et al., 2005; Gifford et al., 2017; Karsten et al., 2013) has not been observed for simulations of place-based maps (Dillon et al., 2021a; Fu et al., 2017; Willis et al., 2020). The present sample included two EAS users with place-based maps that created a spectral gap (PB1 and PB3), though the sizes of those gaps were minimal (PB1: 500-508 Hz; PB3:175-189 Hz). Data for EAS users with placed-based maps and larger spectral gaps are needed to determine the size and frequency range for which a gap may occur before performance is negatively impacted by place-based mapping.

Another factor to consider is electric-on-acoustic masking. For CI recipients of arrays close to or within the region of functional acoustic hearing, the electric current spread from apical electrode(s) may introduce substantial masking of the low-frequency acoustic cues (Imsiecke et al., 2020a, 2020b; Kipping et al., 2020; Koka & Litvak, 2017; Krüger et al., 2017, 2020a, 2020b; Lin et al., 2011). This consideration is increasingly relevant as hearing preservation has been shown in CI recipients of long (e.g., 31.5 mm), flexible lateral wall arrays (Hollis et al., 2021; Mick et al., 2014; Usami et al., 2014). The place-based mapping procedures used in the present study aimed to limit potential electric-on-acoustic masking by reducing the stimulation levels for electrodes at AIDs that were within the region of functional acoustic hearing. While clinically feasible, this method does not take into consideration spread of excitation from electrodes basal to the region of acoustic hearing. Future investigation is needed to determine whether performance with place-based maps would improve using other techniques for avoiding electric-on-acoustic masking.

These preliminary data indicate that electric frequency-to-place mismatches influence the early performance of EAS users, though there are limitations worth consideration. The sample size is not sufficient to assess the relationship between electric mismatches, AID of E1, and other device and mapping variables that have been observed to influence the speech recognition of CI recipients, such as angular separation between the electrodes (Canfarotta et al., 2020; Zhou, 2017), and filter bandwidth (Fu & Shannon, 2002). Participant recruitment is ongoing; a larger dataset will also allow us to consider the differential effects of positive and negative shifts and the influence of electric frequency-to-place mismatches on the binaural hearing for EAS users.

CHAPTER 4: CONCLUSIONS AND FUTURE DIRECTIONS

The experiments reported in this dissertation evaluated whether a strict place-based mapping procedure supported better speech recognition as compared to alternative mapping procedures for EAS simulations and EAS users.

Masked sentence recognition with strict versus full-frequency place-based maps

The first experiment compared the performance of participants with normal hearing listening to CI and EAS simulations with a strict place-based maps or full-frequency place-based maps. A consideration of the strict place-based mapping procedure is that it discards the low-frequency information below the most apical electrode from the electric input. For cases of short (e.g., ≤ 24 mm) electrode arrays with limited functional acoustic hearing (e.g., ≤ 250 Hz), a strict place-based map may result in poorer speech recognition than if that low-frequency information had been provided. Recipients of short electrode arrays may experience a benefit with a *full-frequency* place-based mapping procedure that aligns the mid-frequency information and provides more low-frequency information – though spectrally shifted.

Masked sentence recognition was evaluated for three simulations of short electrode array at shallow AIDs (460º, 389º, and 335º) with strict versus full-frequency place-based maps. The full-frequency map aligned the filter frequencies for the electrodes in the critical speech frequency region only (i.e., 1-3 kHz). The difference between the maps was the distribution of low-frequency information for electrodes below the 1 kHz cochlear region. For the EAS simulations, better performance was observed with the strict place-based map at the deeper AIDs and similar performance was observed between the two maps at the shallowest AID. The implications of the differential performance benefit as a function of AID were 1) the strict place-based map does not result in poorer performance as compared to the full-frequency place-based map for AIDs encountered clinically, and 2) EAS users may experience better performance when the device settings incorporate their individual characteristics (e.g., acoustic hearing, electrode array placement).

The results from experiment 1 and our previous EAS simulation studies (Dillon et al., 2021a, 2022) provide compelling evidence for the effectiveness of a strict place-based mapping procedure over alternative mapping procedures for EAS devices; however, a consideration was that these experiments were conducted with participants who had normal hearing and extremely limited experience listening to each EAS simulation. It was unclear whether these patterns of performance would be observed in adult EAS users, whose performance outcomes are also influenced by other variables, such as duration of severe-to-profound high-frequency hearing loss (Gantz et al., 2016, 2009) and the acoustic hearing level in the implanted ear (Gantz et al., 2016), and may also be influenced by current spread and channel interactions as observed in CI users and simulations (Friesen et al., 2001; Fu & Shannon, 1999a).

Early speech recognition for EAS users with default versus place-based maps

Experiment 2 reviewed the early speech recognition for EAS users randomized at initial activation to listen with a default map or a place-based map. Participants completed tasks of vowel and word recognition at initial EAS activation and the 1-, 3-, and 6-month post-activation intervals. There was a significant main effect of electric frequency-to-place mismatch on speech recognition, with effects observed through 6-months of EAS listening experience. The preliminary data suggest that EAS users experience better speech recognition when electric frequency-to-place mismatches are minimal, and that the negative effects of larger magnitudes of electric mismatches are observed out to 6 months of listening experience. Methods to minimize or eliminate electric mismatches, such as place-based mapping procedures, may support better early speech recognition for the population of patients similar to participants in the present experiment.

These early results in EAS users are consistent with the idea that a strict place-based mapping procedure may support early performance. One remaining question is whether EAS users with default maps may acclimate to the electric frequency-to-place mismatches with longer (i.e., > 6 months) listening experience and achieve similar performance outcomes as EAS users with place-based maps. There is ample evidence of CI simulations and CI users acclimating to electric frequency-to-place mismatches with training and longer period of listening experience (Faulkner, 2006; Fu et al., 2002, 2005; Fu & Galvin, 2003; Li & Fu, 2007; Li et al., 2009; Reiss et al., 2007; Rosen et al., 1999; Sagi et al., 2010; Smalt et al., 2013; Svirsky et al., 2004, 2015b; Vermeire et al., 2015), but less is known about acclimatization to electric frequency-to-place mismatches in EAS users.

Future directions

The next step in this program of research is to evaluate the long-term performance of EAS users listening with default or place-based maps on tasks of monaural and binaural hearing. The negative influence of electric frequency-to-place mismatches may not be fully overcome for EAS users. Also, electric frequency-to-place mismatches may negatively influence the binaural hearing for EAS users by creating interaural mismatches of the auditory information. Interaural mismatches have been shown to negatively influence the binaural hearing abilities of bilateral CI users (Kan, Goupell, & Litovsky, 2019; Kan et al., 2013; Svirsky et al., 2015a). The binaural hearing abilities of EAS users with default versus place-based maps remains unknown. Ongoing work will evaluate the patterns of speech recognition and acclimatization to varying magnitudes of electric frequency-to-place mismatches, the influence of electric-on-acoustic masking, and the effectiveness of place-based mapping for EAS users on measures of monaural and binaural hearing with long-term device use.

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