ABSTRACT

Title of Dissertation:	EFFECTS OF INTERRUPTING NOISE AND SPEECH REPAIR MECHANISMS IN ADULT COCHLEAR-IMPLANT USERS
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The long-term objective of this project is to help cochlear-implant (CI) users achieve better speech understanding in noisy, real-world listening environments. The specific objective of the proposed research is to evaluate why speech repair ("restoration") mechanisms are often atypical or absent in this population. Restoration allows for improved speech understanding when signals are interrupted with noise, at least among normal-hearing listeners. These experiments measured how CI device factors like noise-reduction algorithms and compression and listener factors like peripheral auditory encoding and linguistic skills affected restoration mechanisms. We hypothesized that device factors reduce opportunities to restore speech; noise in the restoration paradigm must act as a plausible masker in order to prompt the illusion of intact speech, and CIs are designed to attenuate noise. We also hypothesized that CI users, when listening with an ear with better

peripheral auditory encoding and provided with a semantic cue, would show improved restoration ability. The interaction of high-quality bottom-up acoustic information with top-down linguistic knowledge is integral to the restoration paradigm, and thus restoration could be possible if CI users listen to noise-interrupted speech with a “better ear” and have opportunities to utilize their linguistic knowledge. We found that CI users generally failed to restore speech regardless of device factors, ear presentation, and semantic cue availability. For CI users, interrupting noise apparently serves as an interferer rather than a promoter of restoration. The most common concern among CI users is difficulty understanding speech in noisy listening conditions; our results indicate that one reason for this difficulty could be that CI users are unable to utilize tools like restoration to process noise-interrupted speech effectively.

EFFECTS OF INTERRUPTING NOISE AND SPEECH REPAIR MECHANISMS IN ADULT COCHLEAR-IMPLANT USERS

by

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Chapter 1: Introduction

To introduce the broad topic of this dissertation, I first discuss how cochlear implant (CI) users are generally impacted by noise and how this affects speech understanding in noisy listening environments. I then describe the ways in which CI manufacturers have attempted to combat the speech-in-noise problem by adding noise-reduction software to CI sound processors. Finally, I discuss a mechanism by which normal-hearing (NH) listeners often repair noise-interrupted speech, called "perceptual restoration," and follow this by reporting how signal degradations introduced by CI processing may decrease perceptual restoration. My goal for this project is to determine the extent to which we can increase speech repair in CI users to ultimately improve communication in everyday listening scenarios.

1.1 Speech-in-noise perception with cochlear implants

The CI is an auditory prosthesis that can restore a sensation of sound. The device works by transforming acoustic signals into electrical pulses, which directly stimulate the spiral ganglion cells and auditory nerve fibers in the inner ear. The Food and Drug Administration (FDA) has approved cochlear implantation in people with severe-to-profound hearing loss for whom hearing aids are no longer useful. The main purpose of the CI is to restore the user's ability to understand speech.

CIs have been approved for implantation in people of nearly all ages, from children as young as one year old to elderly adults ("Fact Sheet: Cochlear Implants," 2010). Generally, the CI is successful in providing the user speech understanding in quiet listening environments (Fetterman & Domico, 2002), dramatically improving the user's ability to communicate through oral language. However, in noisy[1] listening environments like cafés and classrooms, CI users' speech understanding is often reduced. For example, in one study, CI users were only able to understand 64% of sentences in a noisy listening environment, even when the sentences were much louder than the background noise (Balkany et al., 2007). Similar findings have been found for speech recognition in both adult and child CI users (A. Caldwell & Nittrouer, 2013; Fetterman & Domico, 2002), and such performance is quite low compared to how a NH listener would perform under comparable conditions (A. Caldwell & Nittrouer, 2013; Kaandorp, Smits, Merkus, Goverts, & Festen, 2015; Loizou et al., 2009). In a study by Kaandorp et al. (2015), for example, NH adults achieved speech reception thresholds (SRTs) of −4.2 in noisy backgrounds, much lower (i.e., better) than CI users' SRTs of +8.0.[2] Therefore, it appears that CIs are highly susceptible to noise interference, reducing their utility in day-to-day listening environments (Fetterman & Domico, 2002; Fu & Nogaki, 2005; Sladen & Zappler, 2015; Zhao, Stephens, Sim, & Meredith, 1997). To underscore the importance of this problem, in an open-ended questionnaire about the hearing concerns of CI users, difficulty hearing speech in noise was the most reported problem (Zhao et al., 1997), and has continued to be reported as a major problem even with more recent technology (Faulkner & Pisoni, 2013; Gomersall, Baguley, & Carlyon, 2019; Lassaletta, Castro, Bastarrica, de Sarria, & Gavilan, 2006).

[1] For the purposes of this dissertation, "noise" will refer to any unwanted sound (Moore, 2012), including signals like competing speech.
[2] As a comparison with other groups experiencing non-normal hearing, listeners with bilateral hearing aids had SRTs of +0.5 for digits in noise, while NH listeners had SRTs of −9.1 (Bost, Versfeld, & Goverts, 2019).

Several potential factors can reduce a CI user's ability to understand speech in noisy conditions. These factors will be discussed below. First, however, it is important to stress that a CI does not provide a perfect imitation of a functioning, healthy human cochlea, and thus aspects of CI software and hardware can introduce unique problems when users need to communicate in noise. To highlight this, a discussion of how a CI works is essential.

CIs translate acoustic information to electrical information in the following way. Speech sounds are captured by the CI's microphone(s) and then passed through various software algorithms, undergoing a process called "pre-emphasis" (Loizou, 2006). Proprietary "pre-emphasis" algorithms, specific to each CI manufacturer, work to alter and enhance the incoming acoustic signals in a way that is meant to provide the best, most perceptible signal possible to the CI user. A deeper discussion of these "pre-emphasis" algorithms will appear below. Next, these pre-emphasized acoustic signals are sent through a bank of bandpass filters. Each bandpass filter captures acoustic information within a specific band of frequencies; this method is meant to imitate the frequency-based organization of the human cochlea, which also processes an incoming acoustic signal based on frequency. Next, the temporal envelopes of the bandpass filtered signals are extracted. The temporal envelope of a signal is the slow change in amplitude over time, and is one type of timing information available in an acoustic signal. Another type of timing information is called "temporal fine structure." Temporal fine structure encodes the fast-moving amplitude and phase changes in a signal. CI processing typically discards this temporal fine structure and instead only preserves the temporal envelope (Loizou, 2006). Next, compression is applied to each extracted temporal envelope. The goal of compression is to reduce the changes in amplitude (i.e., intensity) present in the signal to a small specific range. While speech signals have large changes in amplitude, a typical CI user can safely utilize only a small range of amplitude changes. Very quiet, just barely audible sound levels are called "thresholds" and uncomfortably, almost painfully loud levels are called "uncomfortable loudness levels." While this range in loudness from threshold to uncomfortably loud is quite large in NH listeners – up to approximately 140 dB (Billings & Gray, 1972) – this range can be as small as 5 dB in some CI users (Loizou, 2006). Thus, compressing the range of possible amplitudes into a CI-user-specific range is important in order to allow some perceptible variation in speech amplitude to be available to CI users. Having access to these changes in speech amplitude is important for discriminating among speech sounds and syllables (Greenberg, Carvey, Hitchcock, & Chang, 2003), especially consonants (Nie, Barco, & Zeng, 2006; Xu, Thompson, & Pfingst, 2005). Next, the compressed temporal envelopes modulate a series of electric pulse trains, and these trains are specific to each frequency band. Finally, these envelope-modulated electric pulse trains are transmitted to the CI user's electrodes, and the pulse trains stimulate the surviving spiral ganglion cells and auditory nerve fibers of the cochlea (Loizou, 2006).

With the idea of how a CI typically works in mind, we can now consider how the processing of speech sounds to electrical impulses may be impacted by noise. The three main factors that I will cover are (1) poor spectral resolution, (2) duration of deafness, and (3) age.

1.1.1 Factors affecting speech-in-noise perception

The CI's poor spectral resolution is one potential cause of poor speech-in-noise understanding among CI users. Spectral resolution refers to how much frequency information about the signal is available; since the signal processing algorithms in the CI discard fine spectrotemporal detail and there are limited channels available to present envelope information, resolution is typically low (Loizou, 2006). While this low resolution may not adversely affect speech understanding in quiet environments, it appears to have a dramatic negative effect on speech understanding in noisy environments. For example, Dorman, Loizou, Fitzke, and Tu (1998) showed that in NH listeners presented a CI simulation (that is, a vocoder), only four channels of spectral information were needed to obtain high sentence understanding in quiet. However, more channels were needed to understand speech in a background of constant speech-shaped noise. When speech was more intense than the background noise, 12 channels were needed; when background noise was more intense than speech, at least 20 channels were needed (Dorman et al., 1998). Thus, a lack of spectral resolution – access to several channels of frequency information – appears to reduce speech-in-noise understanding. This may be because with better spectral resolution, a listener can more easily distinguish speech from noise, as the two are less perceptually similar (Jin, Nie, & Nelson, 2013; O'Neill, Kreft, & Oxenham, 2018).

While some CIs can provide almost two dozen electrodes to the user, research has shown that the number of "effective" channels – that is, the number of channels from which the user can actually derive benefit – at any one time is approximately 8 channels (Friesen, Shannon, Başkent, & Wang, 2001)[3]. This is much lower than the 20 CI simulated-channels

[3] However, see more recent reports by Croghan, Duran, and Smith (2017) and Berg et al. (2019) for a different result, where up to 22 or 16 channels of information (respectively) was useful for CI users perceiving speech in noise. These results may be influenced by CI participants having access to newer CI technology (e.g., pre-curved electrode arrays that have better electrode/nerve interface due to more effective alignment with the modiolus) and better neural survival due to trends in earlier implantation and/or looser criteria for implantation in recent years. CI users with older technology and who were implanted less recently may not be able to achieve such a level of performance.

NH listeners needed in loud noise as reported by Dorman et al. (1998). The amount of spectral information that can be provided by the activated CI electrodes is therefore not necessarily the same as the amount of actual spectral detail a CI user can receive. The health and proximity of the spiral ganglion cells upon which electrodes are supposed to fire, and the amount of current spread from the electrodes, also affect one's effective spectral resolution (Fu & Nogaki, 2005; Fu, Shannon, & Wang, 1998; Oxenham & Kreft, 2014). Current spread occurs when electrical current from the electrodes unintentionally spreads to neurons beyond the target neuron population. When this happens, each electrode is contributing less independent sound information, and resolution suffers.

Beyond affecting speech understanding in steady-state noise environments, poor spectral resolution can also reduce a CI user's ability to obtain release from masking in modulated (i.e., fluctuating) noise (Oxenham & Kreft, 2014). Masking can be defined as a situation where a sound of interest is "made inaudible by the presence of other sounds" (Moore, 2012). Release from masking, then, indicates situations where the sound of interest once again becomes audible, even in the presence of the masking sounds. NH listeners are able to "listen in the dips" of a fluctuating noise masker, gleaning clear bits of speech information with which they can build up their perception of the speech stream in the brief moments when noise volume is reduced. Compared to NH listeners, CI users show less release from masking in a modulated noise masker (Nelson & Jin, 2004; Nelson, Jin, Carney, & Nelson, 2003). The fact that CI users cannot apparently "listen in the dips" underscores the point that CI users generally struggle to access speech information in noisy listening situations to the same degree as NH listeners. Oxenham and Kreft (2014) reported that CI users' poor spectral resolution and the effects of current spread contribute to noise perception differences between CI users and NH listeners, with CI users experiencing smoother temporal envelopes of noise and fewer fluctuations. Having smoother temporal envelopes means CI users have less access to envelope modulations, which are critical for conveying speech information.

Attributes of the CI user him- or herself could also be influencing how well he or she can understand speech in noise. Fetterman and Domico (2002) found that duration of profound deafness was predictive of how well the CI users were able to understand speech in noise. “Durations of deafness” refer to periods during which CI users received almost no audible acoustic input. Fetterman and Domico (2002) concluded that long durations of reduced audible input might result in anatomical and/or physiological changes to the auditory system, which in turn reduce one’s ability to understand speech in noise, perhaps through the deterioration of auditory neurons. Duration of deafness has been shown to be associated with reduced speech understanding in quiet as well, indicating that it is an important factor for hearing-related outcomes in CI users in general (Blamey et al., 2013; Green et al., 2007; Holden et al., 2013).

Another attribute of CI users that could be affecting their ability to understand speech in noise is age. Sladen and Zappler (2015) found that CI users older than 60 years had significantly worse speech understanding in noise and quiet compared to younger CI users. Both age groups were matched for duration of deafness and length of CI use; therefore, age itself appeared to have a unique influence on speech perception. Aging could affect factors like cognition, particularly processing speed, which is important for quickly and accurately processing speech and which slows with age (Lin et al., 2012). Aging is also associated with central auditory pathway changes. For example, aging can reduce accurate and efficient encoding of incoming auditory signals in the central auditory nervous system (Anderson, Parbery-Clark, White-Schwoch, & Kraus, 2012; Gordon-Salant, Fitzgibbons, & Yeni-Komshian, 2011; Ouda, Profant, & Syka, 2015).

To summarize, difficulty understanding speech in noise is the number one concern among CI users (Zhao et al., 1997). The main causes of this difficulty appear to be related to poor spectral resolution, or a lack of access to clear frequency information. The CI's signal processing removes fine spectrotemporal detail (Loizou, 2006), and the effective number of frequency channels available to CI users at any one time is approximately eight (Friesen et al., 2001), much lower than what was needed for NH listeners presented a CI simulation to successfully perceive speech in noise (Dorman et al., 1998). The number and health of neurons in the auditory nerve, their proximity to the stimulating electrode, and the extent of current spread can also impact spectral resolution. In situations where release from masking should be possible, that is, in fluctuating noise (during which listeners should be able to glean speech information during "dips" in the noise), reduced spectral resolution prevents CI users from showing speech understanding improvements (Jin et al., 2013; Nelson & Jin, 2004; Nelson et al., 2003; Oxenham & Kreft, 2014).

Beyond spectral resolution, duration of deafness (Fetterman & Domico, 2002) and age (Sladen & Zappler, 2015) could also be reducing speech-in-noise understanding in CI users. Longer durations of deafness and advanced age could result in physiological and anatomical changes along the auditory pathway, decreasing its ability to clearly encode speech signals in noise, and aging could additionally impair the cognitive skills crucial for processing speech.

1.1.2 Front-end preprocessing in cochlear implants

In the US, three CI manufacturers are currently approved by the FDA for implantation in humans: Cochlear Ltd., MED-EL, and Advanced Bionics (Loizou, 2006). Choice of CI brand is up to the patient, though the patient may be directed toward a certain brand based on surgeon or hospital preference. Each of the three CI manufacturers offer models with similar components, though the specific workings of these components may differ. For example, while all CIs contain an array of intracochlear electrodes for encoding sound information with amplitude-modulated electrical pulse trains, the number of electrodes can vary based on manufacturer. Similarly, while all CIs provide microphones, the number of microphones and their location on the head may differ across brands (Chaikof, 2016). In addition, while all CIs utilize proprietary software strategies in their speech processors, the exact details of these strategies are not public and are specific to each brand.

All three manufacturers have attempted to mitigate the "speech-in-noise problem" in CIs. One way they have done so is by implementing various sound pre-processing algorithms. These algorithms may attempt to remove noise from incoming speech signals prior to sending signals to the electrodes; they can also adjust aspects of the CI microphones and other settings in an attempt to make target speech information more salient. In this paper, these various algorithms will be referred to as "front-end preprocessing."

As mentioned previously, each CI manufacturer has their own proprietary front-end preprocessing strategy. Cochlear Ltd. advertises front-end preprocessing strategies like SmartSound iQ, Wind Noise Reduction (WNR), and Signal-to-Noise-Ratio Noise-Reduction (SNR-NR), all of which are meant to improve speech understanding in noisy, non-optimal listening environments ("The Cochlear™ Nucleus® Implant System," 2018). Similarly, MED-EL advertises Automatic Sound Management and Wind Noise Reduction ("Cochlear Implants," 2017) and Advanced Bionics advertises ClearVoice Speech Enhancement Technology and AutoSound ("AB's Exclusive Sound Processing Technologies," 2018), all of which are also meant to boost and improve speech signals in background noise. Again, the point of all these front-end preprocessing strategies is to partially "solve" the speech-in-noise problem in CIs.

While speech understanding in noise generally improves with front-end preprocessing (Davidson, Geers, & Brenner, 2010; Gifford & Revit, 2010; Rakszawski, Wright, Cadieux, Davidson, & Brenner, 2016; Wolfe et al., 2015), it is possible that individualized algorithm adjustments could improve speech-in-noise perception further. This section will detail front-end preprocessing in Cochlear-brand CIs, as well as research on how these algorithms affect speech understanding in noise. We focus on Cochlear-brand CIs because they are the most common device among the CI population to which we have access. Detailed descriptions of front-end preprocessing that is likely to be engaged during a speech repair paradigm (which involves listening in noise) will be the focus of this section, though other programs will be mentioned briefly.

1.1.2.1 Front-end preprocessing in Cochlear-brand CIs

The first strategy I will discuss is Adaptive Dynamic Range Optimization, or ADRO. ADRO aims to place incoming speech signals into the CI user's dynamic range (Wolfe et al., 2015). The dynamic range is a range of loudness, stretching from the CI user's threshold, or the quietest sound they can hear, to the CI user's maximum loudness level, or the loudest sound they can hear and still feel it is not uncomfortably loud (Gifford & Revit, 2010). Because CI users typically have very small dynamic ranges compared to NH listeners (Blamey, 2005), without ADRO, they could miss important speech information. This is because signals less intense than the user's threshold and more intense than their maximum loudness level would fail to be transmitted.

With ADRO, if a sound in the environment is quieter than the CI user's threshold level, ADRO will boost the volume of that sound, and conversely will reduce the intensity of a sound that exceeds the CI user's maximum loudness level (Blamey, 2005). ADRO adjusts signals within each individual channel, providing a fine-grained adjustment in intensity levels (Gilden, Lewis, Grant, & Crosson, 2015).

Another strategy that responds to loudness is called Automatic Sensitivity Control, or ASC. This strategy adjusts the sensitivity of the microphone(s) of the CI, depending on the level of the ambient noise in the listening environment (Gifford & Revit, 2010). With ASC turned off, sounds are encoded linearly between 25- and 65-dB SPL, after which "infinite" compression turns on. Compression distorts speech signals and makes them more difficult to understand (Rakszawski et al., 2016). With ASC turned on, at very low values of microphone sensitivity, sounds below the CI user's threshold level are not encoded, and sounds above the CI user's loudest comfortable sound level are compressed (Wolfe et al., 2015). As microphone sensitivity increases, the sound level at which compression is engaged decreases, as does the sound level at which signals are not encoded. These microphone sensitivity changes are slow acting, and thus not abrupt (Mauger, Warren, Knight, Goorevich, & Nel, 2014; Wolfe et al., 2015). ASC acts on all channels; it does not make adjustments on individual channels like ADRO (Yathiraj & Rao, 2013).

Another strategy that is related to sound levels is called Whisper. While ASC is slow acting, Whisper is fast to respond to incoming signals (Mauger et al., 2014), boosting the level of quiet or distant signals by 10 dB. This strategy is useful in quiet listening environments, and has been shown to result in significantly better speech understanding in quiet compared to when this program is turned off (Mauger et al., 2014).

ADRO, ASC, and Whisper are all types of Automatic Gain Control (AGC). As stated above, CI users have narrow dynamic ranges, approximately stretching 10 to 20 dB (Khing, Swanson, & Ambikairajah, 2013), which makes encoding the dynamic range of a typical talker, 40 to 50 dB (Zeng et al., 2002), difficult. AGC aims to compress sounds in the environment into CI users' narrow dynamic ranges (Spencer, Tillery, & Brown, 2018). ADRO and ASC are "slow-acting" AGCs, in that they respond over the course of several seconds to changes in level in the listening environment; Whisper is "fast-acting," meaning it can react to changes in the environment on the order of milliseconds (Khing et al., 2013). Fast-acting compression can help shield CI users from loud, brief noises, but may introduce discontinuities or distortions in the amplitude of the incoming signals (Başkent, Eiler, & Edwards, 2009; Khing et al., 2013).

A strategy targeting noise directly is Signal-to-Noise-Ratio Noise Reduction (SNR-NR), which is part of the SmartSound iQ system. SNR is defined as the ratio of the level of the target signal (usually speech) to the level of the noise, with positive SNRs meaning target sounds are more intense than noise, and negative SNRs meaning target sounds are less intense than noise. SNR-NR works by flagging CI channels that seem to be encoding steady-state noise (Wolfe et al., 2015). Working HVAC systems and car engines are examples of steady-state noise producers. The gain of noisy channels is then reduced "instantaneously" (Gilden et al., 2015), as it is assumed that these channels do not contain important acoustic information. SRTs improved in CI users using an early version of SNR-NR, compared to using no SNR-NR strategy, in a study by Dawson, Mauger, and Hersbach (2011). In that study, SRTs improved across all three types of noise tested: speech-weighted noise, party noise, and city noise. These latter two noises were real recordings made at a cocktail party and beside a city street, respectively. However, Dawson et al. (2011) noted a large amount of variability among their participants in terms of SNR-NR benefit, in that some participants showed poorer SRTs with SNR-NR turned on, especially in the more "dynamic" noises – party noise and city noise. Mauger et al. (2014) concluded that SNR-NR was most effective in listening environments where background noise is continuous rather than modulated.

Another strategy targeting noise is Wind Noise Reduction (WNR), which is also part of the SmartSound iQ system. This feature attempts to reduce the harmful effects of wind noise on incoming signals, and could be useful during bicycle riding or when working outdoors (Gilden et al., 2015). If wind noise is detected, WNR changes microphone settings and reduces the intensity of low-frequency information (that is, frequency information below 400 Hz, which is associated with wind noise) that is provided to the CI user (Mauger et al., 2014; Wolfe et al., 2015). Note that some speech energy occurs in this frequency range as well, and thus could be affected by the WNR algorithm. Wind noise is detected by comparing microphone inputs on the CI; if these signals are decorrelated, wind is likely present. Typically, slowly modulated signals like speech should be correlated at the CI microphones, since the microphones are situated close together on the device.

Different microphone settings in general can be helpful in different listening environments, and automatic changes to microphone settings have already been shown to occur with ASC and WNR. They also occur with SCAN, which is discussed next. With the Fixed directional microphone setting (also known as "Zoom"), sounds at specific locations away from the direction in which the CI user is looking are attenuated by 15-20 dB (Gilden et al., 2015). This reduces the intensity of sounds that could be distracting to the CI user, and which are not in his or her direct field of view. With the Adaptive directional microphone setting (also known as "Beam"), the point of attenuation is no longer fixed, and can adapt to new locations, meaning it can adapt to movements of a distracting noise source (Gilden et al., 2015). Finally, with the Standard directional microphone setting, no major attenuation in sounds occurs—attenuation mimics the attenuation experienced by NH listeners, in that sounds toward the side and back of the CI user are reduced slightly in level (Gilden et al., 2015).

The last strategy I will discuss is SCAN, which is a scene analyzer algorithm and part of the SmartSound iQ system. SCAN attempts to detect and classify the type of listening environment the CI user is presently in, and based on this classification alters aspects of sound processing to provide the best listening experience for the CI user (Biever, Gilden, Zwolan, Mears, & Beiter, 2018; Wolfe et al., 2015). Scene types included in SCAN are Speech, Speech in Noise, Quiet, Music, Wind, and Noise. According to Wolfe et al. (2015), SCAN classifies environments by analyzing intensity (loudness), spectral characteristics (e.g., voice pitch), temporal characteristics (e.g., timing information and rhythm), and modulation (changes in intensity across time). Based on the scene classification, microphone settings are changed. For example, when the Speech in Noise scene is detected, the Adaptive microphone (Zoom) is turned on; when Speech or Music scenes are detected, the Standard microphone setting is turned on (Mauger et al., 2014).

Gilden et al. (2015) tested whether SCAN improved speech understanding in 40 unilateral CI users, aged 13.2 to 81.2 years. These CI users were tested on whether their speech understanding in noise improved with the Nucleus 6 sound processor (which includes SCAN) compared to their regular Nucleus 5 sound processor (which does not include SCAN). Speech understanding was tested with sentences presented at 60 dB-A from a loudspeaker directly in front of the participant. Speech-weighted noise was presented at 55 dB-A from a loudspeaker at 90 degrees from the front of the participant, on the side of the participant's CI. The study involved two visits. At the first visit, CI users achieved an average 21.2% correct speech understanding in noise with their usual Nucleus 5 settings, and an average 53.1% correct speech understanding with Nucleus 6/SCAN, a large improvement. After this first visit, the participants took the Nucleus 6 home and used it as their new default CI for four weeks. At the end of the four weeks, the participants completed their second visit, and their speech-in-noise understanding was tested again. With the Nucleus 6/SCAN, participants achieved an average 56.4% correct speech understanding, indicating a stable effect of the benefit of the new processing strategy and device for speech understanding. Subjectively, nearly all of the participants reported that they felt that the Nucleus 6/SCAN improved their speech understanding in quiet and noise, improved their ability to localize sound, and improved sound quality and ease of listening compared to the Nucleus 5.

Mauger et al. (2014) tested whether several of the new features in the Nucleus 6 improved speech understanding in 21 CI users who wore Nucleus 5 as their default sound processor. All participants were post-lingually deafened (i.e., experienced hearing impairment after learning oral language), aged 49 to 90 years, and had worn their CI for 1 to 10 years. Prior to testing, all participants were asked to wear a Nucleus 6 sound processor for a minimum of two weeks. Participants were then tested five separate times, with each experimental session occurring one week apart, on various speech materials in various noise environments. Participants were tested with the default and their preferred Nucleus 5 settings and with six different Nucleus 6 settings. Speech materials included monosyllabic words in quiet and the Australian sentence test in noise. From this latter test, SRTs were calculated by presenting speech at 65 dB SPL and adjusting the background noise level until a level was reached at which participants achieved 50% correct sentence understanding. Lower SRTs were indicative of better speech understanding. The Australian sentence test was presented with two types of noise (speech-weighted noise or 4-talker babble noise) at two possible noise locations (noise at the same location as the target speech [co-located at 0 degrees] or noise at a different location from the target speech [not co-located, presented simultaneously at 90, 180, and 270 degrees from the target, which remained at 0 degrees]).

For speech in quiet, the best performance was with the Nucleus 6/Whisper setting. Since the Whisper program boosts quiet and distant sounds, it makes sense that Nucleus 6/Whisper provided the best speech-in-quiet performance. For SRTs in co-located speech-weighted noise, Nucleus 6/SCAN elicited the highest speech understanding scores, performing significantly better than all other settings. For SRTs in co-located 4-talker babble, no program worked significantly better than any other; this condition appeared to be the most difficult of the noise conditions for CI users. For SRTs in nonco-located speech-weighted noise and 4-talker babble, the best performance was found with settings that allowed microphone directionality changes (i.e., Nucleus 6/SCAN, Nucleus 6/Beam, and Nucleus 6/Zoom). Thus, microphone directionality appears to be key for improving speech understanding in these types of noisy environments. As a reminder, SCAN implements microphone-setting changes based on scene classification.

Finally, the researchers reviewed the logged scene classifications provided by SCAN for the speech-in-noise conditions where noise was co-located with the target. After presenting four sentences with co-located speech-weighted noise, SCAN classified the scene as Quiet for 1/3 of the participants, Noise for 1/3 of participants, and Speech in Noise for 1/4 of participants. By the 20th sentence, almost all participants' SCAN had classified the scene as Noise, despite the fact that the scene was not simply noise but contained speech, too. After presenting four sentences of co-located 4-talker babble, SCAN classified the scene as Speech in Noise for the majority of participants (87%), and Quiet for all other participants; by the 20th sentence, almost all participants' SCAN had classified the scene as Speech in Noise. These logs show that SCAN is slow to classify scenes across participants and is not always a reliable classifier.

To summarize, several front-end preprocessing strategies are introduced by the Nucleus 6, and key strategies that will likely be important to consider with respect to the speech repair paradigm (which involves listening to speech containing either noise-burst or silent-gap interruptions) include ADRO, ASC, SNR-NR, SCAN, and perhaps Whisper. Note that the default settings of the Nucleus 6 sound processor, which is one of the most recent CI sound processors available from Cochlear, make all of the above front-end preprocessing strategies available for adult users (Gilden et al., 2015; Wolfe et al., 2015).

However, poor classification of sound scenes could reduce the chance that the best set of strategies are being utilized by the device at any one time.

1.2 Perceptual restoration

In everyday listening environments, important speech information may be interrupted by noise or competing talkers. A speech repair strategy called *perceptual restoration* can help a listener improve understanding (Bashford, Riener, & Warren, 1992; Başkent, 2012; Verschuure & Brocaar, 1983). The perceptual restoration effect can be quantified as the boost in speech understanding a listener achieves when listening to noise-burst interrupted speech compared to silent-gap interrupted speech. If the sudden disruption and loss of speech information were all that affected speech understanding in realistic environments, we would expect that performance with noise-burst interrupted and silent-gap interrupted speech would be similar. Since performance with noise-burst interrupted speech is actually better in most cases, additional factors must be at work during the processing of noisy speech.

One reason that noise-burst interrupted speech can be easier to understand than silent-gap interrupted speech is that the presence of noise in a signal interruption promotes an illusion of an intact speech stream. The noise acts as a plausible masker of the speech, and the speech seems natural and as if it is continuing *through* the noisy interruption. This "naturalness" and illusory "intactness" improves speech understanding despite the fact that the noise bursts do not actually add any phonetic information to the sentence. The illusion of intactness is so strong that it can be observed in the auditory cortex – the brain has been shown to represent intact versions of a word (presented in quiet) similarly to noise-burst interrupted versions of a word (Leonard, Baud, Sjerps, & Chang, 2016). Silent-gap interrupted speech is comparatively more difficult to understand than noise-burst interrupted speech, even if the same amount of speech is available between interruptions. Silent-gap interrupted speech seems “hoarse and raucous” (Miller & Licklider, 1950), and similar to speech heard through a cellular phone with poor reception. The listener does not perceive an illusorily intact speech signal continuing “through” the interrupting silences.

In general, it is thought that perceptual restoration involves top-down mechanisms interacting with bottom-up acoustic information (Başkent, 2012; Başkent et al., 2016; Shinn-Cunningham & Wang, 2008). The top-down factors that can interact with this bottom-up information include: context usage, or applying one’s knowledge about the context in which the speech is occurring; expectations about the speaker and topic of conversation; and linguistic knowledge like vocabulary and grammatical constraints (Başkent et al., 2016; Ishida & Arai, 2016; Patro & Mendel, 2020; Samuel, 1987; Shinn-Cunningham & Wang, 2008). Furthermore, the presence of noise might provide enough ambiguity to stimulate potential word candidates (Başkent et al., 2016; Bhargava, Gaudrain, & Başkent, 2014), thus leading to a higher chance of successfully identifying the interrupted word. Finally, the presence of noise may also be (1) masking misleading cues generated by the silent-gap condition (e.g., a silent gap being misperceived as a voiceless consonantal stop), (2) masking distortions of the temporal speech envelope caused by the abrupt changes in the signal when speech is turned off prior to an interruption (Bologna, Vaden, Ahlstrom, & Dubno, 2018), and/or (3) maintaining the temporal patterning of speech, leading to easier processing (Powers & Wilcox, 1977).

Adult NH listeners can typically obtain excellent speech understanding in the presence of noise by utilizing restoration (Başkent, 2012; Newman, 2004; Samuel, 1981; Warren, 1970). I will first focus on perceptual restoration in these types of listeners. In later sections, I will discuss the extent to which CI users utilize perceptual restoration.

1.2.1 Early perceptual restoration studies

In this section, I will describe four early studies in the area of perceptual restoration. In the subsequent section, I will describe more recent work on perceptual restoration.

The term "perceptual restoration" was introduced by Warren (1970), who described a study in which young adults restored a missing speech sound in a sentence context when it was replaced by a noisy interruption (a cough) but not when it was replaced by a silent gap. The presented sentence was "The state governors met with their respective legislatures convening in the capital city" and the missing speech sound was the first /s/ in "legislatures." When a cough replaced the /s/, the majority of participants reported that they perceived no missing speech sounds – that is, the majority of participants restored the missing /s/ and heard the cough as an extraneous sound. In contrast, when the /s/ was simply deleted from the sentence, creating a silent gap, all participants were able to detect which speech sound was missing and did not perceive a restored word. In a separate paper, Warren and Sherman (1974) concluded that restoration was a normal, necessary process: without restoration, understanding speech in any realistic, noisy listening environment might be impossible.

Miller and Licklider (1950) reported a study about interrupted speech a few decades before Warren (1970), but did not refer to the phenomenon as perceptual restoration. They were interested in how intelligibility was affected by deletions of speech across time. If speech could be deleted at certain intervals without affecting intelligibility, this method could potentially conserve resources in a speech-transmission system. To test this, they applied a periodic rectangular wave to a speech signal, which had the effect of creating periodic silent gaps, and varied factors that are still important variables in restoration paradigms involving multiple interruptions today. These factors were the frequency of interruption (usually denoted in Hz), the proportion of speech available within each interruption segment (usually referred to as duty cycle), and the temporal regularity of interruptions.

Miller and Licklider (1950) initially tested five NH young adults on their speech understanding of an auditorily presented list of 50 monosyllabic words. Across conditions, the frequency of interruptions was varied, but the duty cycle remained at 50%. This means that if the frequency of interruption was 10 Hz, the first 50-ms of each 100-ms segment contained speech information, and the second 50-ms of each 100-ms segment was interrupted (here, replaced with a silent gap). Participants struggled with interruption frequencies of 1 Hz, after which performance improved as frequencies increased to 100 Hz. Miller and Licklider (1950) concluded that participants struggled with interruption frequencies of 1 Hz because at this rate, large portions of the individual words were missing, for example the entire initial or final consonant. Higher performance at faster frequencies was believed to be due to the fact that participants were provided with several “looks” at each word or even each phoneme. Thus, even though information was deleted, enough “looks” or “glimpses” at the signal were sufficient for participants to interpret the overall phoneme or word.

Another condition in that study varied duty cycle, or the proportion of speech available compared to the proportion of silent-gap interruption within each segment. Having greater proportions of the speech signal available, regardless of interruption frequency, greatly improved speech understanding scores; for example, a duty cycle of 80% resulted in speech understanding of over 80% correct for all tested frequency conditions containing regular interruptions.

While the previous conditions from Miller and Licklider (1950) evaluated word recognition when the word lists were interrupted with silent gaps, they also tested how well participants perceived speech that alternated with noise (i.e., noise-burst interrupted speech). At slower than 5-Hz interruption rates, speech understanding was similar in both noise-burst interrupted and silent-gap interrupted conditions; at faster interruption rates, speech understanding with noise-burst interruptions declined. This is the opposite of the expected restoration effect. Miller and Licklider (1950) did not provide information about how speech and noise were alternated, whether any amplitude envelope ramping between speech and noise was used, or whether there was large variability among their five participants, which could potentially help us interpret their atypical result.

Miller and Licklider (1950) reported that although speech understanding with noise-burst interruptions became poorer than speech understanding with silent-gap interruptions at frequencies above 5 Hz, participants described the noise-burst interrupted speech as “more natural and probably more intelligible.” This sentiment was repeated among participants in another restoration study by Verschuure and Brocaar (1983), who reported noise-burst interrupted stimuli to be “easier to follow” and “continuous.” Miller and Licklider (1950) described this sentiment as the “picket fence” effect. When noise alternates with speech, the speech begins to be perceived as continuous, like scenery observed through the slats of a picket fence. Though the scenery is obviously truly continuous behind the fence, the observer can only see slices of scenery between slats, and must put the image of the scene back together in her mind's eye. The noise interruptions thus served as slats, with enough speech information between that could be used to restore the signal, despite the fact that this notion was not supported by the experimental data (Miller & Licklider, 1950). It is possible that by presenting monosyllabic words, which have no context clues and do not exist in a sentential framework, few top-down mechanisms (context, expectations, etc.) were able to interact with the bottom-up acoustic information to produce a typical restoration effect.

Samuel (1981) investigated perceptual restoration using a paradigm informed by signal detection theory. Previous work in the field had focused mostly on presenting speech with silent-gap or noise-burst interruptions, and then measuring either percent words reported correctly or self-report as to whether the interrupted phoneme was present (Warren, 1970; Warren & Obusek, 1971; Warren & Sherman, 1974). In contrast to these approaches, Samuel (1981) believed that measuring restoration with a signal detection task, and applying signal detection theory to analyze the results, provided a more "direct" measure of the phenomenon.

The signal detection theory framework allows the researcher to separate listener bias from the results using calculations of hit, false alarm, correct rejection, and miss rates (Samuel, 1981). Presenting two types of noise-burst interrupted stimuli – one type where the noise is *added to* the speech, and one type where the noise *replaces* the speech – and asking participants to report whether the presented speech signal was intact, allows the researcher to measure the strength of the restoration illusion (Samuel, 1981). If a listener fails to detect the deletion of the speech signal, as occurs in the noise-replaced condition, then it means that the listener is experiencing the restoration illusion.

Samuel (1981) predicted that if a listener is provided with context, they will have strong expectations about the incoming speech signal, and the listener will need very little bottom-up acoustic information to confirm these expectations[4]. In the first experiment, participants were presented with high-frequency and low-frequency words. A high-frequency word is a word to which listeners are frequently exposed, and thus listeners may have more practice retrieving its representation from their lexicon. A high-frequency word was predicted to be highly restorable, since the brain has more expectations for the word to appear than it does for a low-frequency word. Another variable in this first experiment was the number of syllables in the presented words. Longer-syllable words were predicted to be highly restorable, as more context is provided (and more constraints are made) by words with more syllables. Another variable was phoneme class: it was hypothesized that phonemes that were most acoustically similar to the white noise burst interruption (i.e., fricatives and stops) would be more likely to be restored, due to bottom-up confirmations. Finally, the last variable was the location of the interruption in the word: at the beginning, middle, or end. It was hypothesized that the most restoration would occur for an interrupted phoneme at the end of a word, as the brain would be working with more context prior to the interruption.

[4] Samuel (1981) used the terms "expectation" and "confirmation" to refer to top-down mechanisms and bottom-up acoustic information, respectively.

Participants were asked to identify whether the presented word had a phoneme *replaced* by noise or *mixed with* the noise. *D*-prime values were calculated for the various conditions, a *d*-prime value being an index of how discriminable the added versus replaced versions of the words were. High *d*-prime values meant the participant was able to discriminate between the added and replaced versions, and thus no restoration occurred. Low *d*-prime values meant discriminability was poor, and the participant likely experienced restoration.

The results were as follows. The restoration effect (i.e., low *d*-prime values) was strongest for high-frequency words and for longer, four-syllable words, which revealed an effect of context and expectation on restoration. The restoration effect was also strongest for fricatives and stops, revealing an effect of bottom-up acoustic information on restoration. The predicted effect of context was not observed for the variable of interruption location: restored phonemes were most likely to occur in any position of a word, be it the beginning, middle, or end.

The second experiment by Samuel (1981) compared restoration of non-words and real words, to measure how lexical knowledge affected restoration. The intact (non-interrupted) version of the word or non-word was presented first, and then either a noise-added or noise-replaced version of the same stimulus. Participants were asked to compare the two stimuli and decide which type of interruption had been used in the second stimulus (noise-added or noise-replaced). Participants showed high discriminability for non-words compared to real words and much lower discriminability for real words. Lexical knowledge thus appears to be a top-down mechanism that can affect restoration. In summary, Samuel

(1981) helped demonstrate through a signal detection task that top-down and bottom-up streams of information interact during restoration.

Other early work in restoration includes a study by Bashford et al. (1992). Their study was composed of two experiments, the first investigating the bottom-up acoustic spectral information requirements for restoration, and the second investigating how contextual information affects restoration. For the first experiment, sentences were multiply interrupted (i.e., the same sentence contained several interruptions) with either silent gaps or bursts of five different types of pink noise, each with a different noise-band center frequency (375, 750, 1500, 3000, or 6000 Hz). The narrow-band noise-bands were each 1/3-octave wide. The sentences were filtered so that the maximum speech information was available at 1500 Hz, with the slopes of the low-pass and high-pass filter on either side of 1500 Hz dropping 48 dB per octave. The interruptions were presented at ~2.86 Hz with a 50% duty cycle, and the signal-to-noise ratio (SNR) of speech to noise was −10 dB. The researchers found that speech understanding was maximized with the pink noise-burst interruptions centered on 1500 Hz, and the boost in speech understanding from the silent-gap condition to the 1500-Hz-centered noise condition was 9%. This result, according to the researchers, demonstrated the importance of plausible maskers for restoration: a narrowband speech signal (centered on 1500 Hz) required a narrowband noise burst (centered on the same frequency) to maximize the restoration illusion. For the second experiment, the researchers varied the context available in the interrupted speech. At the "low-context" end of the continuum, they presented monosyllabic word lists. At the "high-context" end of the continuum, they presented highly predictive sentences. They also presented low-predictive sentences, which provide a word in a neutral carrier sentence. The most accurate speech understanding and the greatest restoration effects were found with the highly predictive sentences, followed by the low-predictive sentences. Participants experienced no restoration with monosyllabic words. The researchers concluded that context is important for restoration to work, even if that context does not provide a plethora of semantic information (as occurs in the low-predictive sentences). Syntactic constraints, coarticulation, intonation, and stress could all be useful for speech repair, even if semantic clues are unavailable (Bashford et al., 1992).

In summary, these early studies discovered the phenomena of perceptual restoration and began to probe how and why it occurs through various methodologies like signal detection theory, single word interruptions, and multiply interrupted sentences. More recent work in this area will be discussed in the next section.

1.2.2 More recent perceptual restoration studies

Additional novel methodologies for studying perceptual restoration have been used in recent work in this area. For example, some researchers have investigated the role of the auditory brainstem in restoration, with some advocating a strong role for bottom-up acoustic information in the process, and less for top-down mechanisms (Bidelman & Patro, 2016). Other researchers have advocated for a deeper analysis of speech understanding scores in restoration paradigms. For example, Smith and Fogerty (2017) examined the types of errors participants made during a noise-burst interrupted speech understanding task, rather than a more holistic measure of "percent words correct." They found that at low duty cycles, where less of the speech information is available between interruptions, participants often omitted whole words from their answer (i.e., provided no response) or substituted incorrect words. At high duty cycles, where more of the speech information is available between interruptions, participants most often substituted an incorrect phoneme. While Smith and Fogerty (2017) did not analyze error types in a silent-gap condition, they posit that their methodology could be useful for restoration research, as this could help determine individual differences in restoration benefit.

Benard, Mensink, and Başkent (2014) noted large individual variability in perceptual restoration in NH listeners, even among younger adult listeners, and asked whether linguistic and cognitive skills could account for this variability. Linguistic and cognitive skills are posited as top-down mechanisms that interact with bottom-up acoustic information. Benard et al. (2014) found that NH participants' performance in several of the interrupted (both silent-gap and noise-burst) speech conditions were positively correlated with vocabulary scores (PPVT III), but not with cognition scores (WAIS IV). While Benard et al. (2014) correlated linguistic and cognitive scores with interrupted speech performance, they did not directly correlate these scores with restoration benefits – thus, while it appeared that vocabulary was an important factor for interrupted speech understanding, its exact role in restoration remained unclear.

Jaekel, Newman, and Goupell (2018) also included linguistic and cognitive measures in a restoration experiment, in the hopes that these measures could explain individual differences in restoration benefit. Linguistic skill, quantified as participants' average phonemic and semantic lexical access ability, or how quickly they could generate words with a specific initial speech sound or belonging to a specific semantic category (e.g., "animals"), respectively, was positively correlated with restoration benefits, but only when speech signals were degraded to simulate CI processing (Jaekel et al., 2018).

Cognitive skill, measured with a general working memory task, was not associated with restoration benefit in any speech condition. In contrast, Nagaraj and Magimairaj (2017) found that both receptive vocabulary and verbal working memory were predictive of higher restoration of low-context sentences. There are thus conflicting results about how top-down mechanisms like linguistic knowledge and cognitive abilities moderate restoration and whether they can successfully explain individual variability in restoration benefits.

Finally, another line of recent work has investigated how restoration works in other listener groups besides young NH adults. Interest in how people with hearing loss restore speech is the focus of the following section. The impacts of aging on restoration have been studied also (Bologna et al., 2018; Jaekel et al., 2018; Saija, Akyürek, Andringa, & Başkent, 2014). A study by Saija et al. (2014) showed that older NH listeners experience greater restoration benefits than younger NH listeners, perhaps revealing the important role of top-down mechanisms for the restoration effect. Older NH listeners tend to have larger vocabularies and show better use of context and expectations due to a lifetime of practice with dealing with noisy backgrounds and compensating for missing speech information (Pichora-Fuller, 2008; Sheldon, Pichora-Fuller, & Schneider, 2008), all of which are believed to be important top-down mechanisms. In contrast, neither Bologna et al. (2018) nor Jaekel et al. (2018) found evidence that greater restoration of unprocessed, interrupted speech in older NH adults was correlated with language or cognitive abilities.

1.2.3 Perceptual restoration with degraded input

Perceptual restoration has been shown to be a useful tool for NH adult listeners hearing speech in noisy environments. The extent to which perceptual restoration is accessible to adults without normal hearing, particularly those who use hearing devices like CIs, is the focus of this section. Much of the research in this area has been conducted with NH listeners presented simulations of CI processing rather than with CI users themselves. As discussed previously, difficulties understanding speech in noise is one of the chief concerns reported by CI users; thus, ensuring that perceptual restoration is accessible to this group is important.

1.2.3.1 Perceptual restoration in CI users

CI users struggle to comprehend silent-gap interrupted speech (Chatterjee, Peredo, Nelson, & Başkent, 2010; Gnansia, Pressnitzer, Pean, Meyer, & Lorenzi, 2010). They experience less “release from masking,” or boosts in speech understanding when noise interferers are intermittent rather than constant, than NH listeners presented normal or CI-simulated speech (Jin et al., 2013; Nelson & Jin, 2004; Nelson et al., 2003; Perry & Kwon, 2015). While such “release from masking” paradigms are not perfect correlates of the noise-burst interrupted sentences in a speech repair task (the former *overlays* speech with noise, while the latter *replaces* speech with noise), results from these studies support the idea that CI users likely struggle with speech repair.

Bhargava et al. (2014) measured perceptual restoration in CI users directly. They predicted that CI users would struggle to restore speech because they would have less access to high-quality bottom-up acoustic information during speech repair. First, limitations in CI processing would lead to lower-quality, more degraded signals, since CIs encode only limited spectral information and no temporal fine structure. In the same vein, front-end preprocessing in CIs such as compression can distort the shape of temporal envelopes (Başkent et al., 2009). Second, limitations in peripheral auditory encoding could lead to less well-represented sound information, since some CI electrodes may have poor interface with surviving auditory neurons. Poor interface can be due to the way the electrode array was inserted into the cochlea, and because some areas of the cochlea may have no surviving auditory neurons. Bhargava et al. (2014) predicted that it may be more difficult to integrate top-down knowledge with low-quality bottom-up acoustic information, and thus restoration in CI users may be more likely to fail.

For the experiment, Bhargava et al. (2014) tested 13 Dutch CI users, aged 22 to 65 years. All CI users in the study wore unilateral CIs and had at least 1 year of experience with their devices. The majority of CI users in the study wore Cochlear-brand implants, and all participants had to be high performing with regards to speech understanding (i.e., have at least 70% monosyllabic word recognition in quiet). The researchers also tested 14 Dutch NH listeners, aged 19 to 28 years. The CI users in the study were therefore older on average than the NH listeners. Older age is associated with more restoration in NH adults (Saija et al., 2014) and NH adults presented vocoded speech (Jaekel et al., 2018). Experimental stimuli were everyday Dutch sentences, which were presented at 60 dB-A. Sentences were multiply interrupted with silent gaps or noise bursts at a frequency of 1.5 Hz. Duty cycles were either 50% or 75%, which removed one-half or one-fourth of the speech information in each 666-ms segment of the sentence, respectively. SNRs were either –10-, –5-, 0-, or +5-dB SNR. As a reminder, a negative SNR means that speech is less intense than noise. CI users listened to speech with their regular default sound processor settings. NH listeners were presented stimuli in two conditions: either unprocessed (normal) or 8-channel noise-vocoded. All stimuli were presented in the free field through one loudspeaker directly in front of the listener.

At the 50% duty cycle, CI users showed no significant restoration effect (i.e., no change in speech understanding between silent-gap and noise-burst interruption conditions). In contrast, NH listeners presented normal speech achieved a significant restoration benefit of +8.6 RAUs. RAUs stand for “rationalized arcsine units” and are similar to percentages but have properties making them meet certain criteria for inferential statistics (Studebaker, 1985)[5]. For the same NH listeners presented vocoded speech, no significant restoration benefits were observed. Thus, when only half of the speech information was available in each segment, neither CI users nor NH listeners presented a CI simulation could restore speech. This supported the authors’ prediction that poorer bottom-up information impairs restoration, particularly when only short durations of speech information are available.

A different story emerged when more speech information was available between interruptions. At the 75% duty cycle, CI users achieved a significant restoration benefit of +5.6 RAUs. In contrast to the 50% duty cycle (where a restoration benefit was observed), NH listeners presented normal speech showed no consistent restoration effect with the 75% duty cycle, likely due to ceiling performance; for the same NH listeners presented a CI simulation, no consistent restoration effect was observed, though performance was not at

[5] Arcsine transforms were developed to deal with biases in statistics analyzing percent correct. When scores are constricted by a range, like percent correct (0-100), the possible range of variabilities around mean scores are dependent on the mean. A mean score of 50% affords a large range of score variability around the mean, while a mean score of 5% or 95% results in a compressed range of score variability around the mean. However, arcsine transforms on their own are difficult to interpret. Thus, the rationalized arcsine transform was developed to improve interpretation of transformed scores. RAUs can be interpreted similarly to percentages and extend from approximately −20 to +120. See Studebaker (1985) for a more detailed explanation.

ceiling in this condition. Thus, with a greater amount of speech information available in each segment, CI users can achieve restoration, but NH listeners presented a CI simulation cannot.

Bhargava et al. (2014) next looked into the CI users' individual data. CI users were more likely to get a restoration benefit in the 50% duty-cycle condition if they had better baseline speech understanding scores (that is, better speech understanding with intact, non-interrupted sentences) or longer durations of CI use. In the 75% duty-cycle condition, no demographic information nor baseline speech understanding scores significantly correlated with restoration benefit. The researchers concluded that the high-performing CI users obtaining a restoration benefit at the 50% duty cycle were better able to perceive and encode speech information and/or to utilize the speech information they had access to. The researchers also posited that perhaps CI users did better overall in the 75% duty cycle because a greater proportion of temporal envelopes were left intact, which could have led to more accurate lexical activation. Temporal envelopes are important for CI users as they are one of the few cues available for speech understanding, as temporal fine structure and spectral information are missing or degraded with CI processing.

In summary, Bhargava et al. (2014) showed that (1) when interruptions obscured greater portions of the speech signal, neither CI users nor NH listeners presented a CI simulation could obtain restoration similar to NH listeners presented normal, unprocessed speech, on average. However, some CI users with longer use of their CIs and better overall speech understanding *could* obtain restoration in this difficult speech condition, while the rest of the CI users showed no restoration or a negative restoration effect – that is, better speech understanding with silent gaps than with noise bursts. Bhargava et al. (2014) also showed that (2) when interruptions obscured a smaller portion of the speech signal, CI users could restore speech on average, while NH listeners presented a CI simulation could not. Overall, CI users failed to show typical restoration in scenarios where restoration was possible for NH listeners presented non-vocoded speech. Possible reasons for this reduced restoration in CI users include the following. (1) Noise bursts may initiate compression algorithms, leading to distortions in the speech envelopes prior to and/or after the noise burst (Başkent et al., 2009). Since noise was more frequent in the 50% duty cycle condition, perhaps compression algorithm effects were more likely in that condition. (2) While results from NH listeners with CI simulations could lead one to conclude that CI processing is to blame for a lack of restoration, as it degrades the bottom-up acoustic information, some CI users could restore speech at the 50% duty cycle. Perhaps these CI users had better peripheral auditory encoding, which is necessary for restoration in the most difficult listening conditions (Bhargava et al., 2014).

1.2.3.2 Perceptual restoration in CI simulations (vocoding studies)

Investigating how CI processing may affect restoration has been a focus of research for the Başkent lab group. To pursue this line of work, they have often utilized vocoders to simulate aspects of CI processing. Above, findings from Bhargava et al. (2014) were discussed, which included results from a young NH group of listeners presented an 8-channel noise-vocoder CI simulation. In that study, no consistent restoration was observed across the eight duty cycle × SNR conditions with vocoded speech – the only significant restoration effect was seen with the 75% duty cycle at 0 dB SNR. One possible explanation for the results from Bhargava et al. (2014) is that NH listeners did not have adequate experience or training with vocoded speech, which made them less effective at utilizing top-down strategies to repair it. To test whether training with vocoded speech improves restoration, Benard and Başkent (2014) trained young NH listeners to complete a restoration task with interrupted 8-channel noise-vocoded sentences over the course of five testing sessions in the same one-week period (the exact duration of training in this experiment was not reported by the authors). While both silent-gap and noise-burst interrupted speech understanding improved with training, the size of the restoration benefit did not change. Thus, greater exposure to vocoded speech does not seem to induce greater restoration in NH listeners.

Başkent (2012) tested several spectral resolutions and also simulated electric-acoustic hearing to determine if a certain level of bottom-up acoustic information quality was necessary for restoration of vocoded, interrupted speech. Electric-acoustic hearing refers to a situation where a CI user experiences preserved residual, low-frequency hearing by being implanted with a short electrode array. Participants were young Dutch NH listeners (average age = 22 years). Stimuli were everyday Dutch sentences interrupted with silent gaps or noise bursts at a frequency of 1.5 Hz with a 50% duty cycle. Interrupted sentences were then noise-vocoded with either 4, 8, 16, or 32 channels, with the 4 channel stimuli having very poor spectral resolution, and the 32 channel stimuli having comparatively high spectral resolution. Note that 8 channels of spectral information has been posited as the maximum amount received at any one time by real CI users (Friesen et al., 2001)[6]. For the electric-acoustic hearing conditions, the lowest one-fourth of the

[6] Although see more recent evidence supporting the use of more than 8 channels in CI users with newer devices (Berg et al., 2019; Croghan et al., 2017).

channels in each spectral resolution condition were replaced with low-pass-filtered acoustic speech. Participants also completed an unprocessed interrupted speech condition, in which the interrupted speech signals were not vocoded.

With unprocessed interrupted speech, participants showed a 9% restoration benefit. When speech was degraded spectrally, the restoration benefits decreased, and in the most degraded conditions, disappeared altogether. For the regular CI simulation, significant restoration benefit was seen at the highest spectral resolution only, at 32 channels. For the electric-acoustic CI simulation, significant restoration benefits were seen at the two highest spectral resolutions, 16 and 32 channels. Başkent (2012) concluded that the quality of bottom-up acoustic information is an important aspect of restoration with CI-simulated speech: without quality signals, top-down mechanisms are less able to interact with the bottom-up information. Furthermore, the availability of voicing and pitch cues in the electric-acoustic CI condition could have contributed to better restoration.

To determine the extent to which pitch is important for restoration of degraded speech, Clarke, Başkent, and Gaudrain (2016) used a vocoder that would allow the researchers to vary the strength of a pitch percept in the vocoded speech signals. CI processing provides CI users with temporal pitch cues only, whereas NH listeners have access to temporal and spectral information about pitch (Clarke et al., 2016). This lack of clear pitch information in conjunction with poor spectral resolution in CI users could mean that the speech information between interruptions is less intelligible, and that without pitch, it could be more difficult to link speech information across interruptions[7]. In their

[7] Pitch may only be useful at linking degraded speech signals across noise bursts, not across silent gaps. Ardoint, Green, and Rosen (2014) found no difference in silent-gap interrupted speech understanding with 8-channel noise-vocoded speech (containing no voicing information) compared to 8-channel noise-vocoded speech containing fundamental frequency contour information.

experiment, they varied spectral resolution and pitch availability. They tested 19 young Dutch NH listeners (average age = 23 years) with everyday Dutch sentences. Sentences were vocoded using a non-traditional vocoder, which allowed the researchers to tightly control temporal pitch cues. Speech understanding in five spectral resolutions (unprocessed speech, or 4, 6, 8, or 16 channels of noise-vocoded speech) and two pitch conditions (the signal's fundamental frequency [F0] information was retained or removed) was tested. Interruptions were added to the signals after vocoding, rather than before, as was done in previous studies (Başkent, 2012; Bhargava et al., 2014), meaning speech information was degraded spectrally, but noise bursts were not. Interruptions had a frequency of 2.2 Hz and a 50% duty cycle, and were either silent gaps or bursts of white noise. Clarke et al. (2016) found significant restoration benefits at all spectral resolutions but the poorest resolution (4 channels) when pitch information was available. Significant restoration benefits were only observed in the unprocessed and 16-channel condition when pitch information was not available. Thus, access to pitch information seemed to be a useful cue when speech was degraded, leading to better speech repair. The pitch information in this experiment included information about voicing, which could help with phoneme identification, as well as pitch contours, which can provide information about word stress and prosody (Clarke et al., 2016). Overall, the authors concluded that with enough complementary (though degraded) speech cues, and especially with cues about pitch, restoration should be possible in noisy speech situations processed by a CI.

Note that when Clarke et al. (2016) added interruptions *after* signals were vocoded, which created non-noise-vocoded noise bursts, participants were able to achieve restoration (without pitch cues) at 16 channels. In comparison, Başkent (2012), who added interruptions *before* signals were vocoded, which created noise-vocoded noise bursts, found that participants could only achieve restoration at 32 channels. Jaekel et al. (2018) asked if spectral differences between noise interruptions and speech were important for restoration to occur with degraded signals. Perhaps the non-noise-vocoded noise bursts in the study by Clarke et al. (2016) led to better restoration at lower spectral resolutions because there was more of a perceptible difference, and thus better segregation, of noise bursts from the noise-vocoded speech. Perceptual restoration involves an important trade-off when it comes to the noise-burst interruption conditions: first, noise-burst interruptions that are similar to the missing speech information can act as powerful, plausible maskers (Clarke et al., 2016; Samuel, 1981; Warren & Obusek, 1971); second, noise interruptions and speech need to be perceptually separable, in that the brain needs to be able to detect which portions of the incoming signal are speech segments (Clarke et al., 2016). This latter point may be violated when speech and noise interruptions are too perceptually similar (as they would be with noise-vocoded speech and noise-vocoded noise bursts), reducing restoration.

Jaekel et al. (2018) found that young NH listeners presented CI simulations benefitted from greater spectral differences between speech and noise bursts, while older NH listeners (i.e., aged 60 and older) did not. In that study, young and older NH listeners were presented 16- or 32-channel noise-vocoded sentences, which were interrupted at a 2.5-Hz rate with a 50% duty-cycle with silent gaps, noise-vocoded noise bursts (vocoded with the same number of channels as the speech), or non-noise-vocoded noise bursts (unprocessed white noise). Sentences were in English and were either from the BKB corpus (Bench, Kowal, & Bamford, 1979) or the IEEE corpus (Rothauser et al., 1969). With the

BKB corpus, which contains shorter sentences appropriate for children, young NH listeners could only obtain a restoration benefit with non-noise-vocoded noise bursts. Older NH listeners, in contrast, could obtain restoration benefits with both types of noise.

In the Jaekel et al. (2018) study, older NH listeners obtained significantly greater restoration than young NH listeners, demonstrating that older NH listeners not only perform greater speech repair with unprocessed speech (Saija et al., 2014) but also with degraded speech. While this “aging benefit” for restoration, especially in degraded conditions, seems like a hopeful sign for CI users, many of whom are older and lost their hearing later in life, the Bhargava et al. (2014) study revealed that the older CI users (aged 52 to 65 years) showed negligible restoration. Thus, more work in this area is needed to determine how aging and degraded speech interact during speech repair.

1.2.3.3 Perceptual restoration in other populations with hearing impairment

Başkent, Eiler, and Edwards (2010) were interested in studying perceptual restoration in listeners with mild-to-moderate hearing loss, who also report difficulty understanding speech in noise. Due to damaged inner hair cells, these listeners may experience higher thresholds, increased masking, and reduced spectral and temporal resolution; all of these factors could result in poor-quality bottom-up acoustic information, which could impact the extent to which these listeners can repair noisy speech (Başkent et al., 2010). The researchers measured restoration in 9 NH listeners (aged 23 to 57 years), 9 listeners with mild hearing loss (aged 47 to 83 years), and 9 listeners with moderate hearing loss (aged 64 to 81 years years). Participants in the NH group were required to have pure-tone audiometric thresholds of ≤20 dB HL at 500, 1000, and 2000 Hz. Participants in the mild hearing loss group were required to have thresholds between 26- and 40-dB HL, and participants in the moderate hearing loss group were required to have thresholds between 41- and 55-dB HL, at those same frequencies. Stimuli were sentences interrupted with silence or noise bursts in several configurations of interruption rate, SNR, and duty cycle. To ensure that hearing-impaired listeners had access to audible stimuli, linear amplification was provided. Listeners with mild hearing loss showed significant restoration benefits in several of the configurations, particularly those with low SNRs (where noise was more intense than speech) and 50% duty cycles, which mirrored the results in NH listeners. Listeners with moderate hearing loss showed no significant restoration in any configuration. The amount of restoration benefit was not dependent on percent correct in the silent-gap interrupted conditions for either hearing-impaired group (Başkent, 2010), meaning the amount of speech information that could be gleaned by the listeners between interruptions was not driving the observed restoration effects. Thus, poor restoration outcomes with degraded speech are not specific to CI processing, and speech repair mechanisms appear to be affected by a range of signal quality degradations.

Finally, one study has analyzed how front-end preprocessing in devices for the hearing impaired (hearing aids and CIs) could potentially affect restoration. These devices use compression algorithms to keep signals within the user's dynamic range, which both provides audible signals and protects the wearer from uncomfortably loud sounds. Dynamic ranges are narrower in listeners with hearing impairment than in NH listeners, thus necessitating some kind of compression that can translate a larger range of intensities to a smaller range. Başkent et al. (2009) investigated whether compression algorithms in these kinds of devices could negatively affect restoration. Compression algorithms cannot turn on and off instantaneously in the presence of very quiet or very loud sounds; they thus might affect the temporal envelopes of speech sounds surrounding a noise burst. NH participants were presented speech interrupted with noise bursts, with envelope discontinuities of various durations added before and/or after noise bursts. These types of discontinuities would occur with a compression algorithm with various durations of attack times (onsets) and release times (offsets), as these factors vary in real compression algorithms in CIs and hearing aids. Başkent et al. (2009) found that very brief discontinuities (i.e., amplitude ramps of 10-ms) did not impact restoration, while longer discontinuities reduced restoration and affected the extent to which participants thought speech and noise was continuous. Thus, compression algorithms with long release times in response to sudden noise could be hindering speech repair in hearing-impaired listeners utilizing hearing devices, both in the restoration test paradigm and in realistic, noisy listening environments, and could help explain the atypical restoration observed in CI users.

1.3 Summary and Hypotheses

Cochlear-implant (CI) users struggle to understand speech in noisy, real-world listening environments, reducing their ability to participate in classrooms, restaurants, and playgrounds where noise is common. According to the data logs of 2.4 million listening hours in 1501 CI users of all ages, approximately four hours per day (of approximately 11 total listening hours) were spent in noisy conditions (Busch, Vanpoucke, & van Wieringen, 2017). These conditions can affect children's ability to acquire language and impact adults' professional and personal lives (Busch et al., 2017).

Listening to speech in noise is difficult with a CI because its processing schemes can convey only degraded spectral (frequency) information and only some aspects of temporal (timing, intensity) information – that is, the rich acoustic detail of speech is not available to CI users, making it more difficult to separate out important speech information from noise (Jin et al., 2013; O'Neill et al., 2018). CI manufacturers have attempted to combat the speech-in-noise problem by introducing noise reduction algorithms in the CI front-end preprocessing software. These algorithms were crafted to reduce the impact of noise on the incoming speech signals by evaluating soundscapes, changing microphone sensitivity, boosting quiet speech signals, and other measures. The use of these algorithms generally improves speech-in-noise understanding, but there is still room for improvement (M. T. Caldwell, Jiam, & Limb, 2017). Perhaps tweaks to these algorithms could provide CI users access to mechanisms that allow them to further repair noisy speech signals.

NH listeners may improve their speech understanding in noise by relying on a speech repair mechanism called "restoration." Restoration works via an interaction of incoming bottom-up acoustic information with top-down linguistic and contextual knowledge. Noise-burst interrupted signals may be "repaired" by applying one's knowledge of the conversational context, vocabulary, grammatical constraints, and expectations. In the case of restoration, the interruption itself does not prompt speech repair; it is the interruption *plus the presence of the noise* that prompts repair. The presence of noise in the interruption serves as a plausible masker and creates the illusion of an intact speech signal continuing *through* the noise interruption. Thus, NH listeners show a speech understanding benefit with noise-burst interruptions, but not with silent-gap interruptions.

The previous research on restoration in adult CI users has revealed that they show atypical or negligible restoration in situations where NH listeners show restoration benefits. It is unknown if front-end preprocessing, which aims to remove noise from incoming signals, reduces opportunities for CI users to use speech repair. This project aims to investigate this question and measure whether changes to front-end preprocessing can support speech repair in CI users, and ultimately improve their ability to understand speech in noisy listening environments.

One hypothesis, then, is that noise-reduction algorithms in CI front-end preprocessing are reducing restoration in CI users (Experiment #1). This hypothesis is tempered by the fact that some bilateral CI users, meaning users with two CIs, have a “poorer” and “better” performing ear. This is typically shorthand for how well the ear is encoding sound in the peripheral auditory system—that is, where the CI uses electrical pulses to activate surviving cells in the auditory nerve. Poor encoding could be caused by dead regions of auditory neurons in the cochlea and/or ineffective placement of the CI electrode array. A second hypothesis is that an ear with fewer dead regions and/or better electrode array placement may be better equipped to repair speech due to higher-quality bottom-up signals, and thus may be unaffected by the front-end preprocessing – like compression – that could be affecting the restoration illusion (Experiment #2). A third hypothesis is that an ear with poor encoding may not be able to repair speech at all, as bottom-up signals are too degraded for interaction with top-down linguistic knowledge, when that knowledge is made available (Experiment #3).

To summarize, this project will help us evaluate how CI sound processing strategies affect speech repair. From this work, we could develop individualized front-end preprocessing strategies, dependent on peripheral auditory health and the provision of semantic information, to increase opportunities for CI users to restore degraded, interrupted speech. Improving speech repair in people with CIs will support this population as they communicate and interact with others in realistic listening environments.

Chapter 2: Experiment 1: The impact of front-end preprocessing algorithms on restoration

Understanding speech in noisy listening environments such as restaurants and classrooms is an important part of everyday communication. However, for people with severe to profound hearing loss who have received a CI, understanding speech in noise can be particularly difficult (Fetterman & Domico, 2002; Fu & Nogaki, 2005; Sladen & Zappler, 2015; Zhao et al., 1997). The CI is an auditory prosthesis that can restore a sensation of sound, and typically works well at conveying speech signals in quiet listening environments. However, the ability of the CI to encode speech is negatively impacted by the presence of noise (Fetterman & Domico, 2002; Sladen & Zappler, 2015). Improving CI effectiveness in noisy environments is therefore currently a critical area of need.

One current approach in the field to combat noise interference and improve speech understanding in CI users is to rely on front-end preprocessing algorithms. These algorithms are part of the signal processing in CIs that convert acoustic information into electrical pulses. In so doing, these algorithms are designed to select the most important acoustic information to transmit to the user. Modern processing algorithms also seek to distinguish between sounds of interest and noise, and to reduce this noise prior to transmission (*NIDCD fact sheet: Cochlear implants*, 2016). Generally, these algorithms appear to improve CI users' speech understanding in certain noisy conditions (Davidson et al., 2010; Gifford & Revit, 2010; Gilden et al., 2015; Mauger et al., 2014; Wolfe et al., 2015). However, this approach of using front-end preprocessing algorithms to reduce noise in speech signals may disallow use of a speech-repair strategy called "restoration." Determining whether this is the case is the main purpose of this study.

Restoration can occur when a noise masks part of a speech signal, but the speech is still heard as illusorily intact and is properly interpreted (Warren, 1970). During restoration, listeners can use bottom-up acoustic cues – the preceding and following speech information as well as the noise burst itself – to perceive the speech as continuing intact through the noise burst. Listeners can also use one's knowledge about the rules of language (semantic, syntactic, etc.), expectations, experience, and context to appropriately fill-in the lost speech information (Bashford et al., 1992; Başkent et al., 2010; Bregman, 1990). In summary, repairing noise-burst interrupted speech is possible through restoration, and involves access to bottom-up information and the use of top-down confirmation processes.

NH listeners can obtain excellent speech understanding in the presence of intermittent noise by using this speech-repair strategy (Bashford et al., 1992; Verschuure & Brocaar, 1983; Warren, 1970). CI users, in contrast, often show atypical or negligible restoration ability in similarly noisy conditions (Bhargava et al., 2014). If we discover the underlying mechanisms that influence speech repair and cause its failure in CI users, we could improve speech understanding in noise in CI users and potentially develop improvements to CI speech processing.

Previous research on restoration in CI users has focused on changing qualities of the interruption itself. For example, Bhargava et al. (2014) varied the SNR of the speech and interrupting noise, as well as the percentage of speech that was interrupted. The present study expands our knowledge of restoration mechanisms in CI users by measuring the effects of varying parameters at the level of the device. Device variables are, to some extent, more controllable than the presence of environmental noise (e.g., it is easy to change a program on a CI processor; it is hard to avoid many background noises). Therefore, deeper understanding of restoration in CI users could lead to developing better speech-in-noise processing strategies.

We will test the hypothesis that the locus of restoration failure is at the level of CI front-end preprocessing. Specifically, we hypothesize that restoration in CI users will be worse when front-end preprocessing is turned on compared to when it is turned off; the reason being that these front-end preprocessing features were designed to remove or reduce the impact of noise during speech perception (which could cause noise-burst interrupted stimuli to be perceived more similarly to silent-gap interrupted stimuli). By removing or reducing noise, these algorithms also remove or reduce the salience of the cue that prompts restoration, and thus could paradoxically decrease speech intelligibility in a setting with intermittent noise. The rationale for this study is that we can determine if CI users' deficits in speech restoration are at least partly accounted for by software in the CI itself. It is our expectation that front-end preprocessing features in the CI will decrease restoration ability significantly, eliminating any “useful” aspects of noise used in the speech repair process. New noise reduction strategies that allow for some of these “useful” aspects of noise to become part of CI speech processing could then be conceived.

2.1 Methods

2.1.1 Participants

Eleven bilaterally implanted adult CI users participated in this study. Participant demographics are presented in Table 1. The mean age was 62.8 years (SD=14.1 years, range=32 to 79 years). The average age at onset of non-normal hearing in at least one ear was 26.9 years (SD=18.8 years, range=2 to 55 years), and the average duration of non-normal hearing in at least one ear prior to first implantation was 25.3 years (SD=19.8 years, range=0.5 to 59 years). Participants were native monolingual speakers of American English and self-reported normal or corrected-to-normal vision. All participants used a Cochlear-brand CI in both ears with N6 processors. All participants had had their most recent CI activated for at least 6 months prior to testing, which ensured adequate experience with the devices, especially bilaterally. All participants passed the Montreal Cognitive Assessment (MoCA) with a score of ≥22 (Nasreddine et al., 2005), indicating a lack of mild/moderate cognitive impairment.

Table 1. Participant demographics for Experiment 1.

Participant Variable	Mean	SD	Range
Age (years)	62.8	14.1	32 to 79
Average age at onset of non-normal hearing (years)	26.9	18.8	2 to 55
Average duration of non-normal hearing prior to first implantation (years)	25.3	19.8	0.5 to 59
Vocabulary (age-corrected standard score)	105.6	13.1	93 to 134
Working memory (age-uncorrected standard score)	98.0	12.8	78 to 113
Processing speed (age-uncorrected standard score)	100.2	18.1	63 to 122
Attention (age-uncorrected standard score)	100.7	6.3	95 to 113
Baseline speech scores in the ON condition (in %)	95.6	6.7	82 to 100
Baseline speech scores in the OFF condition (in %)	91.4	8.0	76 to 99

Participants also completed a battery of cognitive tests available from the NIH Toolbox (Gershon et al., 2013), with scores presented in Table 1. The age-uncorrected standard scores were collected for these participants. For working memory ("List Sorting Working Memory Test Age 7+"), the mean score was 98.0 (SD=12.8, range=78 to 113). For processing speed ("Pattern Comparison Processing Speed Test Age 7+"), the mean score was 100.2 (SD=18.1, range=63 to 122). For attention and executive functioning

("Flanker Inhibitory Control and Attention Test Age 12+"), the mean score was 100.7 (SD=6.3, range=95 to 113). Finally, participants completed the PPVT-4 (Dunn & Dunn, 2007), a vocabulary test, with a mean standard score of 105.6 (SD=13.1, range=93 to 134).

2.1.2 Stimuli

Stimuli were 320 declarative sentences (created by the author), which contained 5-12 words with a range of speech sound and semantic content. The sentences were recorded by a female speaker with a Standard American English dialect. Twenty sentences were left "intact" (i.e., uninterrupted by silent gaps or noise) and presented in quiet as a baseline measure. Fifty percent of the remaining sentences (*n*=150) were interrupted with silent gaps by applying a 5-Hz periodic nominally square wave with an 80% duty cycle[8] to the signal, with 1-ms raised cosine on/off ramps. The 80% duty cycle means that within each 200-ms long speech segment, the first 160 ms was left intact and the following 40 ms was replaced with a silent gap. Meyer, Brand, and Kollmeier (2011) reported the average English phoneme durations to be between 103 ms and 255 ms, depending on speaking rate; the 80% duty cycle may remove short-duration phonemes like /b/ and /ɛ/ while having less of an effect on longer-duration phonemes like most vowels. Interruptions always began with a full-duration "on" phase. The remaining sentences (*n*=150) were interrupted with

[8] Pilot testing and previous research (Bhargava et al., 2014) have revealed that duty cycle, or the amount of intact speech in a sentence, impacts restoration. For the present study, the 80% duty cycle was chosen based on pilot testing with four adult CI users. On average, this duty cycle produced a perceptual restoration effect—an improvement in performance with noise bursts compared to silent gaps—of approximately 6% with IEEE sentences. In previous restoration research in NH listeners, a 50% duty cycle has been used (Bashford et al., 1992; Newman, 2004; Powers & Wilcox, 1977; Saija et al., 2014; Verschuure & Brocaar, 1983), though some studies have included other duty cycles (Bhargava et al., 2014; Bologna et al., 2018). In the present study's pilot testing, other duty cycles (50, 60, 70, and 90%) produced no restoration effect on average. The overall average accuracy at the 80% duty cycle, collapsed across interruption types, was 64% (SD=27%).

speech-shaped noise bursts instead of silent gaps. The noise bursts were not modulated by the speech envelope that would have appeared in the missing speech segment. Though speech-envelope-modulated noise bursts have been shown to increase restoration (Shinn-Cunningham & Wang, 2008) over and above non-modulated noise bursts, noise bursts encountered in a naturalistic listening environment would be non-modulated, and thus our method provided more of a realistic challenge to participants attempting to restore speech. Noise bursts were presented at 65 dB SPL with a −10-dB SNR, meaning that noise bursts were 10 dB more intense than the average level of the target speech signal. This negative SNR was chosen because previous literature has shown that negative SNRs are typically necessary for the strongest restoration effects to occur and are more likely to prompt the auditory illusion of speech "continuing" through noise (Bhargava et al., 2014). Logically, a noise that is less intense than speech would not "mask" the speech, and thus the illusion of continuity is less likely to occur (Başkent, 2012).

2.1.3 Equipment

Stimuli were presented through two modes: one mode with several front-end preprocessing features turned on (ON condition) and one mode with these front-end preprocessing features turned off (OFF condition). Participants wore two research N6 CI sound processors, for which features can be adjusted to be on or off. Each participant's own clinical maps were uploaded to the research processors prior to the experiment. Stimuli were presented in the free field from two loudspeakers.

In the ON condition, several noise reduction algorithms could affect speech processing. These included SCAN (a scene analyzer that adapts microphone directionality), SNR-NR (a noise reduction algorithm), and WNR (a wind noise reduction program). SCAN automatically detects information about the listening environment and initiates specific programs for enhancing speech understanding based on the scene selected (e.g., Speech, Music, and Speech in Noise). These programs may change microphone settings, and the scene classifier is updated about every second (Z. Smith, Cochlear Ltd. research scientist, personal communication, July 12, 2018). However, SCAN's classifications do not always properly identify the sound environment presented (Mauger et al., 2014), potentially introducing variability across and within listeners in how noise is processed during restoration. SNR-NR and WNR both attempt to reduce background noise and irrelevant loud sounds; these algorithms thus may affect how the noise bursts—the key to restoration—are perceived alongside the speech segments. The SNR-NR program attempts to detect which frequency channels in the CI contain continuous noise, like a generator or the sound of a car’s engine. The channels below a certain SNR are then attenuated (Z. Smith, personal communication, July 12, 2018). This attenuation process, and potential sluggishness in the way the algorithm is applied, could lead to over-attenuation of several channels during and/or after the presentation of a quick noise burst. This over-attenuation could be leading to reduced perceptual restoration. The WNR program detects decorrelation of sound signals recorded between a single sound processor’s microphones, the presence of which is potentially indicative of turbulence from wind. This program likely has little effect during the restoration paradigm, though it is technically a noise-reduction algorithm.

Two more components were activated in the ON condition: ADRO (adaptive dynamic range optimization) and ASC (auto-sensitivity control). These front-end preprocessing strategies were expected to create compression effects (Gilden et al., 2015; Wolfe et al., 2015). Compression could change the relationship between speech and noise signals during noise burst conditions, perhaps by changing the effective SNR. As mentioned previously, in typical restoration paradigms, a negative SNR is needed for the illusion to occur (Başkent, 2012), so changes in the effective SNR could reduce the perception of the illusion. ADRO works by slowly changing the channel gains based on input from the listening environment, which could, over time, impact the effective SNR. ASC is one adjustable loop of the tri-loop AGC (automatic gain control) in Cochlear-brand CIs and works by attempting to reduce signal intensity. Other aspects of AGC and how it could be influencing restoration will be described more in depth in Experiment 2. In that study, we investigate the extent to which AGC may be negatively affecting restoration ability in CI users.

In the OFF condition, SCAN, SNR-NR, WNR, ADRO, and ASC were turned off. Comparing speech understanding results between the ON and OFF conditions allows us to examine the effects of SCAN, noise reduction, and some compression algorithms on restoration. These changes in listening mode, which involved changing front-end preprocessing settings from the CI users' typical programming settings, were expected to have minimal negative impact on uninterrupted speech understanding in quiet, unlike, for example, a change to a frequency-to-electrode allocation, which would necessitate training and time for adaptation.

Finally, a standard omnidirectional microphone setting was used in OFF conditions, with the Fixed and Adaptive (Beam) modes turned off. This ensured that all participants in were using the same microphone setting in this condition, and that microphone characteristics were not automatically changing during the experiment (as could occur with Adaptive/Beam). The standard omnidirectional microphone does not apply level attenuation to any incoming signals, from any direction, beyond what would occur in a NH listener – that is, slight attenuation from the sides and back of the listener. In contrast, the Fixed and Adaptive (Beam) microphones attenuate noise either from any direction besides 0 degrees (Fixed) or from any direction (Adaptive [Beam]). In the ON conditions, SCAN was able to adjust microphone settings.

2.1.4 Procedure

Order of listening mode (ON vs. OFF) was counterbalanced across participants. The first ten sentences in each listening mode were intact, containing no interruptions. All other sentences (n=300) were randomly assigned to listening mode and interruption type (silent gap vs. noise burst) for each participant. Therefore, any sentence had an equal chance of being presented in either of the two listening modes and with either of the two interruption types.

Participants were seated in a soundproof booth (Industrial Acoustics, Inc., New York, NY), one meter away from a pair of loudspeakers located at ±45° from the seated participant. Loudspeakers were calibrated using speech-weighted noise to 55 dB SPL. The experimenter sat in the booth with the participant and controlled the presentation of sentences.

On each trial, one sentence was presented, and participants reported aloud what they heard. Responses were recorded on a voice recorder and graded in terms of number of words correct. Grading was lax, in that incorrect verb conjugations were accepted, similar to the grading used in Jaekel et al. (2018). To ensure accurate grading, a second grader separately graded a subset of responses (*n*=8 participants) by listening to the voice recordings. Inter-rater reliability was 88.1% based on number of sentences agreed on. Inconsistencies were resolved by averaging the scores of the two graders for that specific trial.

2.2 Results

Before adding interruptions to stimuli, participants completed baseline intact speech understanding measures in both the ON and OFF conditions (results presented in Table 1). In the ON condition, average speech understanding was 95.6% (SD=6.7%, range=82 to 100%). In the OFF condition, average speech understanding was 91.4% (SD=8.0%, range=76 to 99%). Per a paired-samples *t*-test, intact speech understanding in the OFF condition was significantly poorer than in the ON condition, $t(10)=4.19$, $p=0.002$.

Prior to the main analysis, correlations among the participant variables (see Table 1) were analyzed to determine which variables could be feasibly included in the mixed effects model. Including highly correlated variables in the mixed model analysis can cause the model to be less stable and lead to higher standard errors. The variables entered into the Pearson correlation analysis were: age, average age at onset of non-normal hearing, average duration of non-normal hearing prior to first implantation, average baseline intact speech score, age-corrected standard scores on the PPVT-4 (vocabulary test), and age-uncorrected standard scores for the NIH toolbox tests of processing speed, working memory, and attention/executive functioning.

Age significantly negatively correlated with processing speed (r=−0.81, p=0.003), and attention (r=−0.78, p=0.004), and significantly positively correlated with vocabulary score (r=0.72, p=0.013); thus, older participants tended to have poorer processing speed and attention skills but stronger vocabularies. Average onset of non-normal hearing significantly negatively correlated with average duration of non-normal hearing (r=−0.73, p=0.011), meaning that participants who experienced hearing loss later in life tended to have shorter durations of deafness. Processing speed significantly positively correlated with attention (r=0.75, p=0.008) and significantly negatively correlated with vocabulary (r=−0.82, p=0.002). No other correlations were significant. Because so many participant variables were found to be correlated, a principal components analysis was conducted in order to create components that were uncorrelated with one another and could be added to the mixed effects model. Principal components analysis with varimax rotation revealed that age, vocabulary, attention, and processing speed were all loading as a single component (Eigenvalue = 3.4). Average age at onset of non-normal hearing and average duration of non-normal hearing loaded as a second component (Eigenvalue = 1.9). Based on this analysis, the first component (age, cognition, and vocabulary), the second component (hearing history), working memory score, and average baseline intact speech scores were retained for mixed effects modeling.

In addition to these components and participant variables, the variables of interruption type (effect coded: −.5 for silent gaps, +.5 for noise bursts), front-end status (effect coded: −.5 OFF, +.5 ON), their interaction, and their interactions with the components and participant variables were included in the mixed effects model. Components and participant variables were standardized and centered so that a score of 0 represented the average of the sample, and scores of −1 and +1 indicated one standard deviation from the mean. Model building followed recommendations from Hox, Moerbeek, and van de Schoot (2018).

The final reduced model for Experiment 1, presented in Table 2, included the fixed main effects of interruption type, front-end status, working memory score, and average baseline intact scores. The following interactions were also included: interruption type × front-end status and front-end status × working memory. The components for age, vocabulary, and cognition and for hearing history were not significant and were not included in the reduced model. The model also included the random intercept for participant and the random participant slopes of interruption type and front-end status. These random effects indicated that participant intercepts explained 29% of the variance, interruption effects across participants explained 10% of the variance, front-end status effects across participants explained 2% of the variance, and 58% of the variance was left unexplained (residual).

Table 2. Final reduced mixed effects model for Experiment 1. SG = silent gaps. NB = noise bursts.

Fixed Effects	**Coefficient**	**SE**	***t***	***p***
Intercept	0.598	0.058	10.34	<0.001*
Interruption type *(effect coded = −.5 SG, .5 NB)*	−0.159	0.036	−4.40	0.001*
Front-end status *(effect coded = −.5 OFF, .5 ON)*	−0.049	0.025	−1.95	0.07
Average intact score (standardized)	0.189	0.028	6.75	<0.001*
Working memory (standardized)	0.083	0.030	2.80	0.03*
Interruption type × Front-end status	0.045	0.021	2.13	0.03*
Front-end status × Working memory	0.084	0.021	3.99	0.003*

Random Effects	**Variance**	**SD**
Participant intercept	0.036	0.191
Interruption type slope	0.013	0.115
Front-end status slope	0.003	0.056
Residual	0.072	0.269

Figures 1 and 2 display individual and average data from this experiment. Figure 1 shows speech understanding in percent correct, and Figure 2 shows perceptual restoration effects in percent, calculated as performance in the silent-gap condition subtracted from performance in the noise-burst condition. As a reminder, the two independent variables in this study were interruption type and front-end status. Interruption type significantly affected performance, with scores for noise-burst interrupted sentences approximately 15.9% lower than scores for silent-gap interrupted sentences (p=0.001; see Figs. 1 and 2). This is the opposite of the expected restoration effect, where we would expect to see better performance with noise-burst compared to silent-gap interruptions. Front-end status was not significant as a main effect (p=0.07; Fig. 1), but did significantly interact with interruption type (p=0.03). The interaction indicated that in the ON condition (compared to the OFF condition), the performance gap between noise-burst interrupted and silent-gap interrupted sentences shrank by 4.5%. This was driven mainly by an increase in scores with noise-burst interrupted sentences in the ON condition (Fig. 1). The hypothesized effect was that noise-burst interruption performance would be *greater* than silent-gap interruption performance, particularly in the OFF conditions; instead, the opposite effect was found. Since the ON condition should, in theory, reduce the level of the interrupting noise, making noise-burst conditions similar to silent-gap conditions, it is perhaps unsurprising that performance was more similar across interruption types in the ON condition.

Figure 1. Individual (*n*=11) and mean speech understanding scores for Experiment 1. Scores with silent-gap interrupted sentences are in gold, and scores with noise-burst interrupted sentences are in red. Scores in the ON conditions are in a darker hue, and scores in the OFF conditions are in a lighter hue. Mean data is presented on the right. SG = silent gaps. NB = noise bursts.

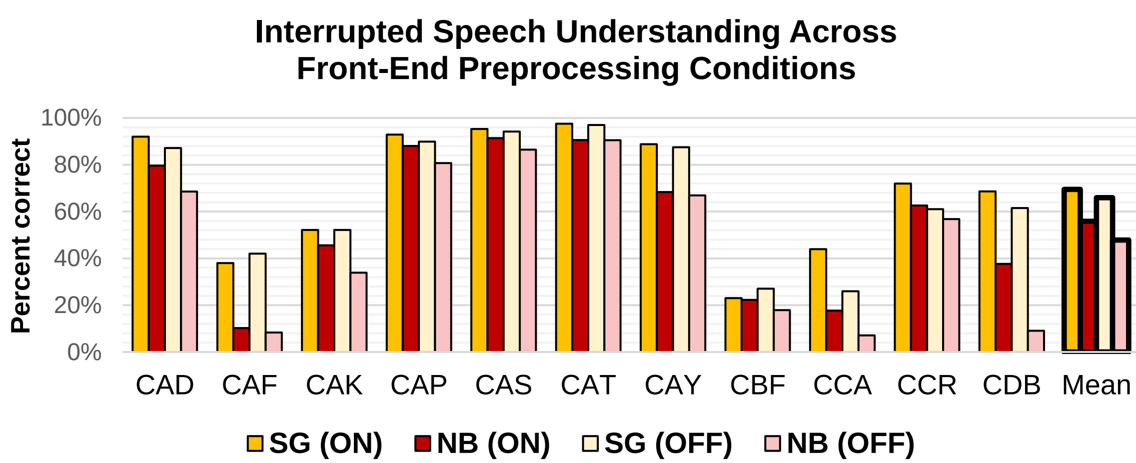
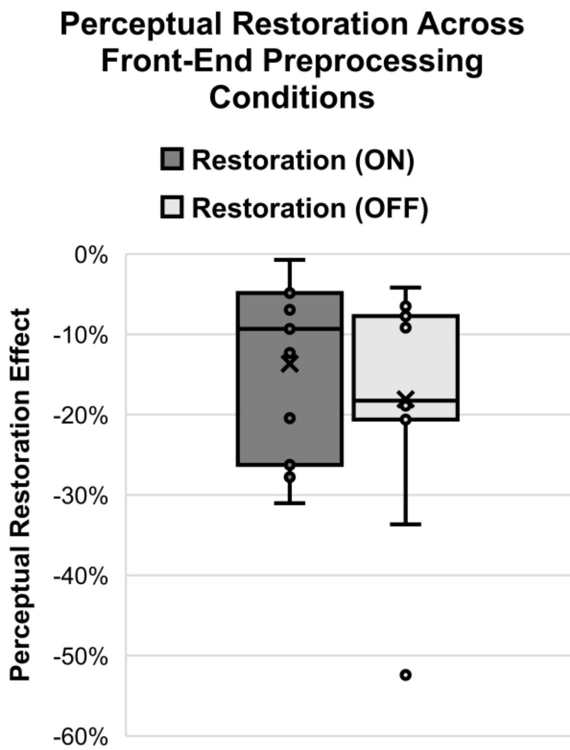


Figure 2. Perceptual restoration effects in ON (dark) and OFF (light) conditions. Circles indicate individual data, the × symbol indicates the mean, and the line within the boxplot indicates the median. The top whisker indicates the maximum value, and the bottom whisker indicates the minimum value; the top of each box indicates the third quartile, and the bottom of each box indicates the first quartile. A circle beyond the whiskers indicates an outlier.



Among participant variables, the following had significant main effects. Average baseline intact speech score was a significant main effect (p<0.001), meaning that for each 1-SD increase above the average intact score for the sample, performance on the experiment overall increased by 18.9%. That is, individuals who were better able to interpret speech in general also were better at doing so in the presence of interruptions. Working memory was also a significant main effect (p=0.03), meaning for each 1-SD increase above the average working memory score for the sample, performance on the experiment overall increased by 8.3%. The interaction of front-end status and working memory was also significant (p=0.003). For each 1-SD increase above the average working memory score for the sample, performance in the ON condition increased 8.4%, meaning that participants with higher working memory scores performed particularly well in the ON compared to the OFF conditions.

Looking at individual data (Figs. 1 and 2), it was clear there was a wide range of performance on the task. While the average trends were consistent across participants (e.g., no participant scored better with noise bursts than with silent gaps; only one participant scored better with OFF than with ON, with all other participants scoring better with ON than with OFF), the variability should be noted. For the noise-burst conditions, performance ranged from 9 to 91% correct. For the silent-gap conditions, performance ranged from 25 to 97% correct. For high-performing participants (n=6)—those whose overall task performance was above 50%—the difference between noise-burst and silent-gap performance was 10.4%: noise-burst performance was 77.5%, and silent-gap performance was 87.9%. In contrast, for lower-performing participants (n=5)—those whose overall task performance was below 50%—the difference between noise-burst and silent-gap performance was 22.5%: noise-burst performance was 21.0%, and silent-gap performance was 43.4%. Thus, lower-performing participants showed a larger gap in performance for noise-burst interrupted versus silent-gap interrupted speech conditions.

2.3 Discussion

This experiment aimed to evaluate whether front-end preprocessing strategies in the Cochlear N6 processor negatively impacted perceptual restoration in CI users. Two surprising results emerged. First, we were unable to detect restoration ability in any of our CI users. Unlike Bhargava et al. (2014), who found that CI users could restore speech in certain conditions with benefits of approximately 8.8%, and unlike results from our own pilot testing with four CI users, we found that noise bursts acted as interferers rather than facilitators for speech understanding in the perceptual restoration paradigm. On average, performance with noise bursts was 15.9% lower than with silent gaps. Second, while front-end preprocessing strategies did not impact perceptual restoration (as perceptual restoration was not observed in either the ON or OFF conditions), noise-burst interrupted speech was most improved by access to front-end preprocessing strategies. Improvements from the OFF to ON conditions for noise-burst interruptions was 8%, while improvements for silent-gap interruptions were only 3%. If our hypothesis about restoration had been supported, the opposite effect would have occurred: performance with noise-burst interrupted speech would be negatively impacted by front-end preprocessing strategies, not enhanced. In actuality, the front-end preprocessing served its intended purpose, even with interrupted speech: it improved speech-in-noise perception. The real question, then, is why noise bursts, compared to silent gaps, was always harmful rather than helpful for CI users. The illusion of restoration, and its benefit for speech understanding in realistic listening environments, rests on the idea that noise serves a useful rather than harmful purpose, at least when it does not further degrade the speech signal itself.

Of the components and participant variables, only working memory scores helped explain front-end preprocessing effects; no components and participant variables helped explain interruption effects. We developed two components based on participant variables: one component was composed of participant age, vocabulary score, processing speed, and attention; the second component was composed of duration of non-normal hearing prior to first implantation and onset of non-normal hearing. Both components made logical sense: it is unsurprising that older age is related to higher vocabulary scores and poorer cognitive abilities (Drag & Bieliauskas, 2010; Park et al., 2002). Furthermore, it is logical that many participants with early onsets of non-normal hearing would also be the participants with longer durations of non-normal hearing prior to implantation, as early implantation of children did not become common practice until fairly recently. Unfortunately, neither of these components helped explain effects in this experiment, and were not even significant predictors of general performance (i.e., they were not significant main effects). While it was predicted that age and interruption type would interact in a way that would benefit noise-burst interrupted speech performance, as was observed in work by Jaekel et al. (2018) and Saija et al. (2014), this was not the case in the present study. Aging is thought to be associated with better perceptual restoration because older adults can draw on the vocabularies they have developed over a lifetime to process speech, as crystallized intelligence like vocabulary is believed to be unaffected by aging processes, unlike some cognitive functions (Saija et al., 2014). However, older CI users in the present study did not show extra ability to utilize the perceptual restoration effect, as was observed in older NH listeners presented unprocessed (Saija et al., 2014) and vocoded (Jaekel et al., 2018) speech. Furthermore, greater vocabulary knowledge or stronger linguistic skills (apart from age) have previously been shown to be associated with greater amounts of restoration, at least in NH listeners presented unprocessed speech (Bashford et al., 1992; Benard et al., 2014), and to a lesser extent in NH listeners presented vocoded speech (Jaekel et al., 2018). Taken together, aging and vocabulary appear to affect interrupted speech understanding differently in CI users compared to NH listeners. While they are helpful factors among NH listeners, they are not predictive of interrupted speech understanding in CI users. Collison, Munson, and Carney (2004) reported that adult CI users appeared to show less of an effect of linguistic processing on speech recognition skills, concluding that the poor-quality input CI users experience makes it more difficult for them to link incoming speech sounds to representations in their lexicons. Perhaps the addition of interruptions to speech stimuli, as occurred in the present experiment, made this process even more difficult, disallowing the use of vocabulary and other crystallized intelligence during the restoration task in our older adult CI users.

Working memory interacted with front-end status, but did not interact with interruption type. The latter finding is perhaps unsurprising when considering previous work in this area, which has shown that working memory did not mediate restoration in younger- or older-NH listeners presented unprocessed speech or vocoded speech (Benard et al., 2014; Jaekel et al., 2018). Instead, in the present study, working memory interacted significantly with front-end status, meaning that compared to people with average working memory scores, CI users with higher working memory achieved particularly higher performance in ON, compared to OFF, conditions. Purdy et al. (2017) similarly found a "trend" where CI users with higher working memory scores achieved higher speech-in-noise understanding with specifically SNR-NR turned ON compared to OFF. CI users with lower working memory scores, in contrast, showed no differences in performance between the two SNR-NR conditions (Purdy et al., 2017). Perhaps CI users with lower working memory scores in the current study are generally negatively affected by the distortions introduced by interruptions, regardless of type of interruption. Comparatively, CI users with higher working memory can effectively process interrupted speech that is less distorted (presumably the ON condition produces a signal that is less changed by the presence of noise interruptions) but fail to do so in the more distorted condition (OFF condition), when working memory resources may be particularly taxed (Finke, Büchner, Ruigendijk, Meyer, & Sandmann, 2016). Research in the hearing aid literature, cited by Purdy et al. (2017), seems to support the idea that listeners with hearing loss and higher working memory scores are more resistant to distortions in speech signals (Arehart, Souza, Baca, & Kates, 2013; Ohlenforst, Souza, & MacDonald, 2016).

In summary, we cannot conclude whether front-end preprocessing strategies affect restoration in CI users, as we were unable to detect restoration in our sample. Interestingly, noise-burst interrupted speech performance was improved by access to front-end preprocessing strategies, but not by enough to overtake performance with silent-gap interrupted speech. There are several possibilities that could explain these findings: (1) front-end preprocessing strategies do not negatively impact noise-burst interrupted speech processing via noise-reduction and compression effects, (2) participants found the general quality of the speech signal to be improved with the front-end preprocessing strategies turned on, and thus were more able to effectively process the difficult noise-burst interrupted speech, or (3) since almost all participants' daily maps included access to at least some of the front-end preprocessing strategies, experience with speech processed in this way resulted in better noise-burst interrupted speech performance in this condition. A final possibility is that other aspects of CI processing outside of controllable front-end preprocessing algorithms prohibited the ability of these CI users to restore speech. Thus, perhaps other areas of interest in the speech processing pathway – namely, the quality of peripheral auditory encoding and/or the access to semantic information – may better serve to promote restoration in these listeners.

Chapter 3: Experiment 2: Measuring effects of presentation level and peripheral auditory encoding on restoration

The intensity of speech stimuli, especially in relation to noise bursts, is important for the restoration effect to occur in NH listeners (Bashford et al., 1992; Başkent, 2012). It is important that noise bursts be perceived as louder than speech in this paradigm, as the noise is then more able to serve as a plausible masker of the speech and promote an illusion that speech is continuing through the noise, intact and uninterrupted (Başkent, 2012). Previous work has analyzed how noise burst intensity affects restoration in CI users: Bhargava et al. (2014) studied how CI users restored meaningful Dutch sentences interrupted with either silent gaps or noise bursts at various SNRs. Speech was always presented at 60 dB(A), and noise was presented at either 55, 60, 65, or 70 dB(A), which is equivalent to +5-, 0-, –5-, or –10-dB SNRs. Contrary to the hypothesized importance of negative SNRs for restoration, CI users showed no variation in restoration effects across SNRs: at the 50% duty cycle, no restoration was observed at any SNR; at the 75% duty cycle, the restoration effect was similar at every SNR. Thus, CI users were not showing typical, expected effects of level differences between speech and noise during the restoration task.

One aspect of CI processing that could be affecting the results observed by Bhargava et al. (2014) is the role of automatic gain control (AGC). Because the dynamic range for a CI user is smaller compared to that of a NH listener, compression is necessary to convey speech signals in the range from audible to comfortable loudness (Khing et al., 2013). The SNRs presented by Bhargava et al. (2014) may not have been perceived as such by the CI users due to this dynamic compression from the AGC. Fast-acting AGC will respond quickly (<10 ms attack time) to sudden loud noises like a door slam, while slow-acting AGC will adjust the intensity of the incoming speech signals over time (Khing et al., 2013). The level at which AGC begins to compress the signal in Cochlear-brand CIs is around 70 dB SPL (Z. Smith, personal communication, July 12, 2018). Therefore, the most negative SNR measured in the study by Bhargava et al. (2014), which contained noise bursts at the 70 dB(A) level and is the SNR that we would expect to show a large, prominent restoration effect, may have been impacted by compression, reducing the perceived loudness differences between speech and noise bursts. Besides the general presence of AGC in the processing algorithm of the CI, the speed with which the AGC turns on/off could also impact restoration mechanisms (Başkent et al., 2009). On/off changes distort the amplitude envelope of speech, and resulted in reduced restoration in NH listeners presented vocoded speech (Başkent et al., 2009). Thus, our hypothesis was that CI users may experience a reduced restoration effect when noise bursts engage AGC, due to envelope distortions and changes to the effective SNR, compared to when noise bursts are less intense and do not engage AGC.

Experiment 2 investigated how AGC affected restoration and added the further element of how AGC and peripheral auditory encoding – that is, the transmission of the electrical signals to various regions of the auditory nerve – interacted to affect restoration. Bilateral CI users often report having a poorer-performing and a better-performing ear (Kan, 2018). For the present study, the poorer-performing ear was expected to have poorer electrode/nerve interface, resulting in poorer-quality bottom-up acoustic information due to less effective encoding of the incoming signals. Additional methods used to classify better ears and poorer ears include the extent of neural survival, order of implantation, ease of telephone use, and etiology of hearing loss (Kan, 2018; Litovsky, Parkinson, Arcaroli, & Sammeth, 2006). Our second hypothesis was that perhaps AGC has less of an impact on restoration in better-performing ears, which can better encode differences between speech and noise, regardless of SNR. AGC is based on the signal and a maximum knee-point level (approximately 70 dB SPL), and is not determined with reference to the individual's own hearing.

3.1 Methods

3.1.1 Participants

Twelve bilaterally implanted adult CI users participated in this study. Information about these participants is presented in Table 3. The mean age was 64.3 years (SD=14.4 years, range=32 to 81 years). Because this study tested each ear separately, Table 3 presents age at onset of non-normal hearing and non-normal hearing duration prior to implantation for each ear individually. Participants were native monolingual speakers of American English and self-reported normal or corrected-to-normal vision. All participants used Cochlear-brand CIs in both ears with N6 processors. All participants had had their most recent CI activated for at least 6 months prior to testing, ensuring adequate experience with the devices. All participants passed the Montreal Cognitive Assessment (MoCA) with a score of $\geq$22 (Nasreddine et al., 2005), indicating a lack of mild/moderate cognitive impairment.

Participants also completed a battery of cognitive tests available from the NIH Toolbox (Gershon et al., 2013). The age-uncorrected standard scores were collected for these participants. For working memory ("List Sorting Working Memory Test Age 7+"), the mean score was 98.6 (SD=12.4, range=78 to 113). For processing speed ("Pattern Comparison Processing Speed Test Age 7+"), the mean score was 98.8 (SD=17.8, range=63 to 122). For attention and executive functioning ("Flanker Inhibitory Control and Attention Test Age 12+"), the mean score was 100.8 (SD=6, range=94 to 113). Finally, participants completed the PPVT-4 (Dunn & Dunn, 2007), a vocabulary test, with a mean age-corrected standard score of 105.8 (SD=12.5, range=93 to 134).

Table 3. Participant variables for Experiment 2.

Subject	Age at Testing (years)	Age at onset of non-normal hearing (years)		Duration of non-normal hearing prior to first implantation (years)		"Better Ear" based on Intact Sentence Scores at 55 dB SPL	Average Intact Sentence Scores Difference between Better/ Poorer Ears (%)	Processing Speed Score (age-uncorrected standard score)	Working Memory Score (age-uncorrected standard score)	Attention Score (age-uncorrected standard score)	PPVT Score (age-corrected standard score)	MoCA Score (out of possible 30 points)
		L	R	L	R							
CAD	79	55	55	8	14	Left	3.7	63	97	96	126	29
CAF	72	3	3	51	56	Right†	N/A†	101	97	99	104	28
CAK	73	35	57	22	12	Right*	3.1	99	78	97	104	26
CAP	49	39	39	1	0	Left*	1.9	122	113	109	96	29
CAS	55	33	33	11	15	Left*	2.2	103	105	94	97	27
CAT	32	10	10	13	8	Left	0.1	122	97	113	93	26
CAY	61	35	32	18	16	Left*	9.4	115	101	106	111	29
CBC	81	6	70	68	6	Right*	20.5	84	105	101	107	28
CBF	61	5	5	47	52	Left*	14.5	99	82	97	99	24
CCA	79	13	70	60	1	Right†	N/A†	74	113	95	134	28
CCR	70	2	2	58	60	Right	1.5	101	82	98	99	29
CDB	60	28	28	13	21	Right	7.9	103	113	104	99	27
Average	**64.3**	**22.0**	**33.7**	**30.8**	**21.8**	**-**	**6.5**	**98.8**	**98.6**	**100.8**	**105.8**	**27.5**
St. Dev.	**14.4**	**17.6**	**25.3**	**24.0**	**21.6**	**-**	**6.6**	**17.8**	**12.4**	**6.0**	**12.5**	**1.6**
Range	**32 - 81**	**2 - 55**	**2 - 70**	**1 - 68**	**0 - 60**	**-**	**0.1 – 20.5**	**63 - 122**	**78 - 113**	**94 - 113**	**93 - 134**	**24 - 29**

*Best-performing ear did not match self-reported "better ear."
†Second ear was not tested in experiment due to <50% correct intact baseline scores.

3.1.2 Stimuli

Stimuli were 580 sentences (created by the author). The design of the experiment was two ear presentations (poorer, better ear) × four interruption/level conditions (speech at 55 dB SPL with silent gaps, speech at 65 dB SPL with silent gaps, speech at 55 dB SPL with 65 dB SPL noise bursts, speech at 65 dB SPL with 75 dB SPL noise bursts), for a total of eight conditions. The condition with speech at 55 dB SPL and noise at 65 dB SPL tested restoration below the AGC knee-point, meaning AGC was not expected to be engaged; the condition with speech at 65 dB SPL and noise at 75 dB SPL tested restoration above the AGC knee-point, meaning AGC was expected to be engaged. The engagement of AGC was expected to change the effective SNR by compressing peaks of incoming sound signal to reduce overall levels; such compression could weaken the illusion of speech continuing through noise and ultimately decrease restoration. Additionally, participants completed a baseline (intact speech) condition and two control conditions (speech at 55 dB SPL with 75 dB SPL noise bursts, and speech at 65 dB SPL with 65 dB SPL noise bursts). The control conditions were necessary for confirming that any restoration observed in the test conditions was not due solely to speech presentation level (i.e., perhaps speech at 65 dB SPL is just generally easier to restore than speech at 55 dB SPL, regardless of SNR). It is not possible to deactivate the AGC, unlike the other front-end preprocessing features (see Experiment 1); thus, we needed to manipulate the intensity of our presented stimuli to analyze the effects of AGC on restoration.

For the eight main test conditions, 480 of the 580 sentences were allotted. The sentences were interrupted following the paradigm described in Experiment 1, generating 240 silent-gap interrupted sentences and 240 noise-burst interrupted sentences at an 80%

duty cycle. One-hundred-twenty sentences of each interruption type were presented to each ear, termed the “poorer” or “better” ears. Sixty sentences of each interruption type, at each ear, had speech presented at 65 dB SPL, and sixty sentences had speech presented at 55 dB SPL. For noise-burst interrupted sentences, the noise was presented at –10-dB SNR, based on the average level of the speech.

For the baseline test, 20 intact sentences were presented to the poorer ear and 20 to the better ear. Ten of these sentences presented to each ear were presented at 55 dB SPL, and ten were presented at 65 dB SPL. For the control conditions, the remaining 60 sentences were allotted to the following conditions. Fifteen sentences with speech presented at 55 dB SPL and noise-burst interruptions at 75 dB SPL were presented to the poorer ear and the better ear (n=30). Fifteen sentences with speech presented at 65 dB SPL and noise-burst interruptions at 65 dB SPL were presented to the poorer ear and better ear (n=30). Results from these control conditions were expected to help identify speech presentation level effects versus SNR effects. The summary of sentence types and presentation conditions is presented in Table 4.

Table 4. Design of Experiment 2.

	Speech at 55 dB SPL	Speech at 65 dB SPL
Poorer ear	• **10 intact sentences** • **15 control sentences** (noise-burst interrupted; noise at 75 dB SPL) • **60 experimental sentences** (silent-gap interrupted) • **60 experimental sentences** (noise-burst interrupted; noise at 65 dB SPL)	• **10 intact sentences** • **15 control sentences** (noise-burst interrupted; noise at 65 dB SPL) • **60 experimental sentences** (silent-gap interrupted) • **60 experimental sentences** (noise-burst interrupted; noise at 75 dB SPL)
Better ear	• **10 intact sentences** • **15 control sentences** (noise-burst interrupted; noise at 75 dB SPL) • **60 experimental sentences** (silent-gap interrupted) • **60 experimental sentences** (noise-burst interrupted; noise at 65 dB SPL)	• **10 intact sentences** • **15 control sentences** (noise-burst interrupted; noise at 65 dB SPL) • **60 experimental sentences** (silent-gap interrupted) • **60 experimental sentences** (noise-burst interrupted; noise at 75 dB SPL)

3.1.3 Equipment

Participants completed half of the experiment with their self-reported "better" ear only and completed the other half of the experiment with their self-reported "poorer" ear only. During the task, participants wore a calibrated research N6 processor, containing the participants' clinical maps associated with that ear with all front-end preprocessing algorithms turned on, in the target ear. Participants removed the CI from the non-target ear. Participants who reported residual acoustic hearing had the ear(s) with residual hearing plugged.

3.1.4 Procedure

Participants were seated in a soundproof booth, with the same setup as that described in Experiment 1. The order of the four listening blocks was randomized for each participant. The four listening blocks were combinations of poorer vs. better ear presentation and speech at 55 dB SPL vs. speech at 65 dB SPL (see Table 4). Within each block, the first ten sentences were intact, containing no interruptions and presented in quiet. The next fifteen sentences were the associated control sentences for that block, containing noise-burst interruptions. The next 120 sentences were the test sentences, 60 of which contained noise-burst interruptions and 60 of which contained silent-gap interruptions. Sentences were randomly assigned to condition and interruption type; any sentence had an equal chance of being presented in any of the four listening conditions as an intact sentence, control sentence, or test sentence. To ensure accurate grading, a second grader separately graded a subset of responses (n=7 participants) by listening to the voice recordings. Inter-rater reliability was 88.0% based on number of sentences agreed on. Inconsistencies were resolved by averaging the scores of the two graders for that specific trial.

3.2 Results

3.2.1 Main Findings

Prior to the main analysis, correlations among the participant variables were analyzed. Including highly correlated variables in the mixed model analysis can cause the model to be less stable and lead to higher standard errors. The variables entered into the Pearson correlation analysis were: age, age at onset of non-normal hearing for each ear, average duration of non-normal hearing prior to implantation for each ear, age-corrected standard scores on the PPVT (vocabulary test), and age-uncorrected standard scores for the NIH toolbox tests of processing speed, working memory, and attention/executive functioning.

Age significantly negatively correlated with processing speed (r=−0.82, p=0.001), and attention (r=−0.73, p=0.008), and significantly positively correlated with duration of non-normal hearing in the left ear (r=0.59, p=0.045) and vocabulary score (r=0.68, p=0.015). Older listeners therefore tended to have poorer cognition, better vocabularies, and a longer period of non-normal hearing in one of their ears. Processing speed significantly positively correlated with attention (r=0.72, p=0.009) and significantly negatively correlated with vocabulary (r=−0.80, p=0.002). Duration of non-normal hearing in the left ear was significantly negatively correlated with age at onset of non-normal hearing in the left ear (r=−0.80, p=0.002), and, similarly, duration of non-normal hearing in the right ear was significantly negatively correlated with age at onset of non-normal hearing in the right ear (r=−0.77, p=0.003). Finally, duration of non-normal hearing in the right ear was significantly negatively correlated with working memory (r=−0.59, p=0.044), and age at onset of non-normal hearing in the right ear was significantly positively correlated with vocabulary (r=0.64, p=0.026).

Principal components analysis with varimax rotation revealed that age, attention, processing speed, and vocabulary were all loading as a single component (Eigenvalue = 3.6, Percent of variance = 36.1%). This component indicated that older age was associated with better vocabulary, slower processing speed, and poorer attention skills. Onset of non-normal hearing and duration of non-normal hearing in the left ear, as well as average baseline intact score, loaded on a second component (Eigenvalue = 2.3, Percent of variance = 23.4%). This component indicated that shorter durations of non-normal hearing in the left ear was associated with later onsets of non-normal hearing in that ear, as well as better average baseline intact speech scores. Onset of non-normal hearing and duration of non-normal hearing in the right ear, as well as working memory score, loaded on a third component (Eigenvalue = 2.2, Percent of variance = 21.9%). This component indicated that, like the second component, shorter durations of non-normal hearing in the right ear was associated with later onsets of non-normal hearing in that ear, as well as higher working memory scores. These three components were included in the mixed effects model analysis.

This experiment aimed to compare effects across ears, to determine the impact of peripheral auditory encoding on perceptual restoration in different compression conditions. Unfortunately, two of the 12 participants (CAF and CCA) were unable to complete testing in their poorer ear, due to very low intact speech understanding scores in that ear. Thus, CAF and CCA only contributed data to the better ear condition. For the rest of the sample, ear differences in performance were not large on average: average interrupted speech scores with the better ear were 51%, and average interrupted speech scores with the poorer ear were 47.5%, a difference of only 3.5%. When this smaller sample's data (n=10 participants) were entered into a mixed effects model containing the random intercepts of participant and ears within participants and the fixed main effects and interactions of ear presentation, interruption type, and level, the main effect of ear presentation was not significant (p=0.11), nor were any interactions with ear presentation (p values ranged from 0.10 to 0.60). With this in mind, the ear effect was dropped from the analysis, and only the better ear scores were ultimately analyzed, which maintained our sample size of 12.

Results for the mixed effects model analysis are presented in Table 5. Individual and average results are plotted in Figure 3, and perceptual restoration effects are plotted in Figure 4. The mixed effects model (Table 5) revealed the following. First, overall performance in the study was 51.3% correct. Noise-burst interruptions significantly decreased performance compared to silent-gap interruptions ($p<0.001$; see Fig. 3), the opposite of the restoration effect. Increasing the intensity of the stimuli from 55 to 65 dB SPL did not significantly change overall performance ($p=0.13$); however, level and interruption type did significantly interact ($p=0.03$). Performance with silent gaps decreased from 57.6% to 55.3% as level increased from 55 to 65 dB SPL, while performance with noise bursts increased from 43.0% to 46.4%.

In terms of participant variables (i.e., components), only component 2 was found to have a significant effect on performance: with each 1-SD increase in scores on this component, overall performance increased by 15.2% ($p=0.002$). As a reminder, higher scores on component 2 were associated with shorter durations of non-normal hearing in the left ear, later onsets of non-normal hearing in the left ear, and better average baseline intact speech scores. Finally, variability in participant intercepts explained 40% of the variance in the study, participants' interruption type, level, and interruption type × level effects each explained 2 to 4% of the variance in the study, and 52% of variance was left unexplained (residual).

Table 5. Results for the mixed effects model analysis for Experiment 2. SG = silent gaps. NB = noise bursts.

Fixed Effects	**Estimate**	**SE**	***t***	***p***
Intercept	0.513	0.067	7.61	<0.001*
Interruption type *(effect coded = −.5 SG, .5 NB)*	−0.117	0.023	−5.15	<0.001*
Level *(effect coded = −.5 55 dB SPL, .5 65 dB SPL)*	0.032	0.020	1.63	0.13
Component 2 *(Left Ear Duration/Onset & Average Intact Score)*	0.152	0.044	3.43	0.002*
Interruption type × Level	0.058	0.025	2.32	0.03*

Random Effects	**Variance**	**SD**
Participant intercept	0.054	0.233
Interruption type slope	0.005	0.071
Level slope	0.003	0.056
Interruption type × Level slope	0.003	0.053
Residual	0.069	0.263

Figure 3. Individual and average results for Experiment 2, in the better ear only. Performance with silent gaps is in gold, and performance with noise bursts is in red. Dark gold and dark red represents performance in the condition where speech was presented at 55 dB SPL; pale gold and pale red represents performance in the condition where speech was presented 65 dB SPL. SG = silent gaps. NB = noise bursts.

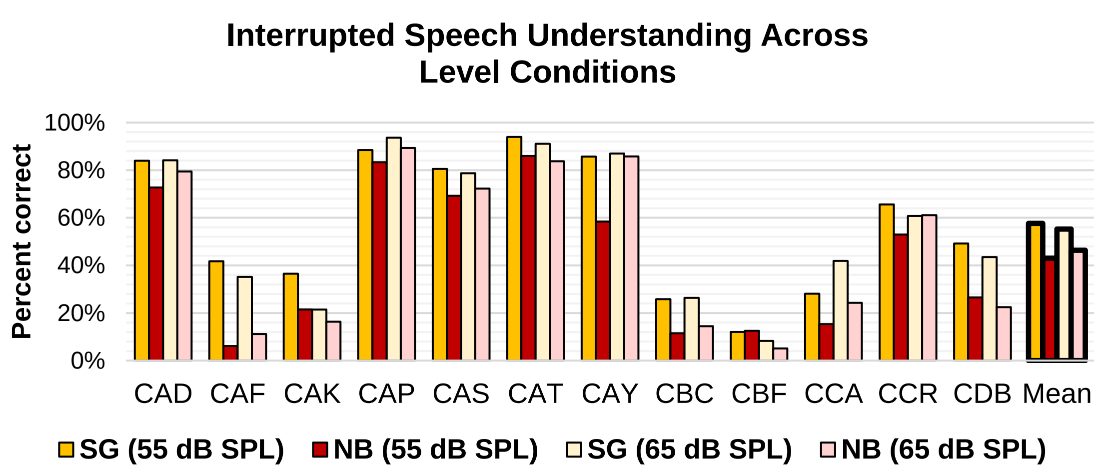
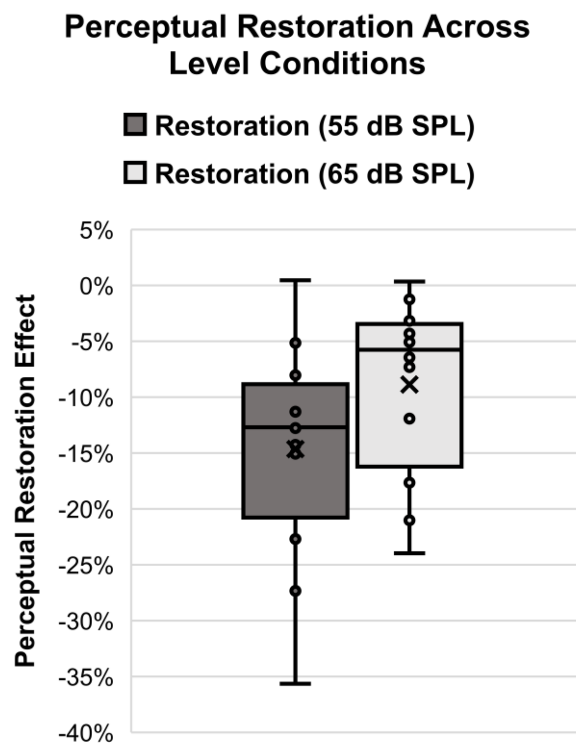


Figure 4. Perceptual restoration effects across level conditions in Experiment 2. Circles indicate individual data, and the × symbol indicates the mean for each condition. The line within each boxplot indicates the median for each condition.

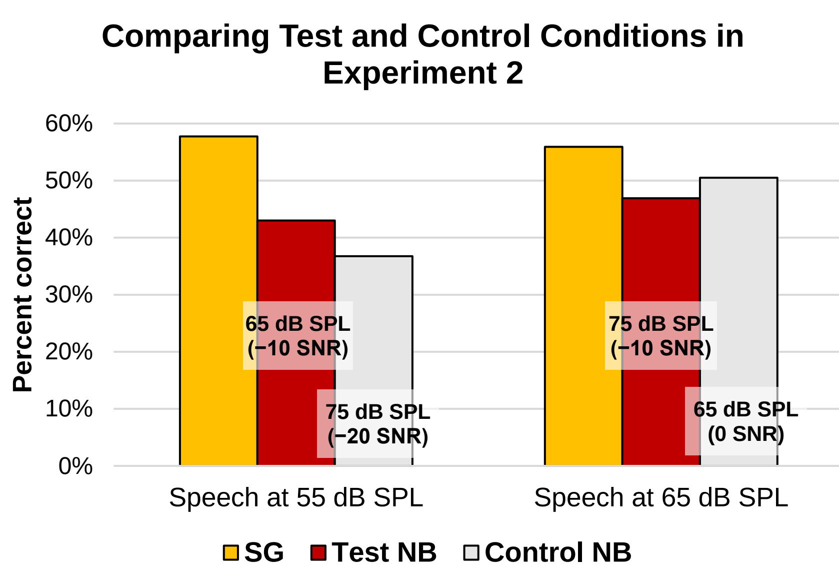


Overall, we could not confirm restoration effects either above or below the AGC knee-point in the better ear (see Figs. 3 and 4). That is, noise-burst performance was never higher than performance with silent-gap interrupted speech in the more intense conditions engaging AGC (65 dB SPL conditions) and the less intense conditions not engaging AGC (55 dB SPL conditions), on average. On an individual level, two participants showed a small perceptual restoration benefit: CBF in the 55 dB SPL condition (0.5% benefit) and CCR in the 65 dB SPL condition (0.3% benefit). Individual variability in performance across participants was also observed, with participants' overall average scores ranging from 9% to 89% correct, and average restoration effects ranging from −30 to −1%.

3.2.2 Control Conditions

We aimed to test whether presenting noise above the AGC knee-point affected restoration; however, by changing our stimuli from 55 dB SPL to 65 dB SPL, we were also changing the intensity of both the noise and the speech signal. Thus, control conditions were presented to participants to test whether more intense speech and/or more intense noise were generally easier to restore. Results from these control conditions are presented in Figure 5.

Figure 5. Average results from test and control conditions, separated by speech presentation level. Test results with silent-gap interrupted speech ("SG") are presented in gold. Test results with noise-burst interrupted speech ("Test NB") are presented in dark red. Control conditions (*n*=15 sentences per condition) with noise-burst interrupted speech ("Control NB") are presented in gray. White boxes indicate the noise level and SNR of noise bursts compared to the associated silent-gap condition.



The best noise-burst interrupted speech performance occurred when speech was more intense (65 dB SPL, compared to 55 dB SPL; see Fig. 5) and noise was equivalently intense (i.e., had a 0 dB SNR). Performance dropped slightly when the level of speech was maintained at 65 dB SPL but noise bursts grew more intense, decreasing to a −10 dB SNR. Performance with noise-burst interrupted speech decreased overall when the level of speech was less intense (i.e., 55 dB SPL). At this speech level, performance was better with a less negative SNR (i.e., −10 dB SNR) compared to a more negative SNR (i.e., −20 dB SNR). Based on results from these control conditions, more intense speech signals in the context of noise-burst interruptions may be easier to understand (though in the context of silent-gap interruptions, performance with more intense speech signals appears to decrease; see Fig. 5). Furthermore, engaging AGC – that is, presenting noise bursts at 75 dB SPL – appears to always decrease performance with noise-burst interruptions, regardless of the level of the speech. Changing the level of the noise but keeping the level of the speech constant, and, conversely, changing the level of the speech but keeping the level of the noise constant, did not reveal equivalent performance across conditions. Therefore, in general, the level of speech information does not seem to be driving restoration; speech at 55 dB SPL or 65 dB SPL does not appear to be particularly more restorable, and noise at 65 dB SPL or 75 dB SPL does not appear to be particularly more restorable. Our main findings likely reflect a change in performance resulting from changing both speech and noise, together, from both being below the AGC knee-point to crossing the AGC knee-point.

3.2.3 Poorer Ear Performance

Ten of twelve participants were able to complete the experimental task in their poorer ear. Poorer ear performance was characterized, unsurprisingly, by overall lower performance. Compared to the better ear, the restoration effect in the poorer ear at 55 dB SPL was −12% (compared to the better ear's −15%). In this condition, silent-gap performance was 1% lower and noise-burst performance was 4% lower in the poorer ear than in the better ear. The restoration effect in the poorer ear at 65 dB SPL was −7% (compared to the better ear's −9%). In this condition, silent-gap performance was 5% lower and noise-burst performance was 7% lower in the poorer ear than in the better ear. Thus, restoration effects were quite consistent across the two ear conditions. The most stable performance across ears was at 55 dB SPL with silent gaps, and the least stable performance was at 65 dB SPL with noise bursts. As mentioned above, when these data were entered into a mixed effects model, neither the main effect of ear presentation nor any interactions with ear presentation were significant. For this sub-sample, then, impacts of peripheral auditory encoding differences between ears did not interact with AGC effects or interruption types.

3.3 Discussion

The restoration illusion requires the presence of a plausible masker within a speech signal interruption (Bashford et al., 1992; Başkent, 2012), usually in the form of a noise that is louder than the surrounding speech. Compression in CIs, which occurs via an algorithm called AGC and is necessary due to dynamic range constraints in CI users, may generally change the intensity of noise in relation to speech and distort speech envelopes

(Başkent et al., 2009; Khing et al., 2013). Both of these factors could reduce restoration when AGC turns on at the knee point of 70 dB SPL.

This study tested 12 participants to detect whether restoration ability was reduced when speech and noise stimuli straddled the AGC knee point vs. when speech and noise stimuli were presented at levels below the AGC knee point. Furthermore, ears were tested separately to detect whether peripheral auditory encoding interacted with compression effects. Previous research has reported that bilateral CI users may have a "better" and "poorer" performing ear, potentially due to differences in electrode/nerve interface (Kan, 2018; Litovsky et al., 2006). The overall hypothesis was that AGC might be less negatively impactful on restoration in a "better" ear, as the ear should presumably be better able to encode speech information and would be less affected by distortions introduced by compression.

Only ten participants were able to complete the task in both ears; two participants had such poor performance in their poorer ears with intact uninterrupted sentences that it was not reasonable to test them with interrupted sentences. For the main analysis, only the better ear data were analyzed, so that data from all tested participants could be included. We found that, similar to Experiment 1, restoration was not observed on average (Figure 4). That is, speech understanding with noise-burst interruptions was generally much poorer than with silent-gap interruptions. Two participants technically showed restoration benefits, one with speech at 55 dB SPL and one with speech at 65 dB SPL, but these restoration benefits were extremely small.

Differences between silent-gap and noise-burst performance shrank when stimuli straddled the AGC knee point, and appeared to be primarily driven by improvements in the noise-burst interruption condition. Thus, when compression was engaged, with all its potential concomitant envelope distortions, the processing of noise-burst interrupted speech actually improved, contrary to our hypothesis. Our participants generally showed improved performance with smaller SNRs (see 0 dB SNR control condition in Fig. 5), so perhaps reductions in the effective SNR due to compression was actually helpful in the 65 dB SPL level test condition. This potential influence of SNR on restoration performance was not observed by Bhargava et al. (2014), who presented CI users with a range of SNRs, from −10 to +5. While NH listeners require negative SNRs to perceive a noise as a plausible masker and thus prompt the restoration illusion, CI users may need positive SNRs in order to successfully process noise-burst interrupted speech. Future research presenting positive SNRs in a restoration paradigm to CI users would help confirm this notion. Furthermore, having access to more intense speech information in the 65 dB SPL conditions appeared to be helpful, at least in the context of noise-burst interruptions (see Fig. 5). More intense speech, compared to less intense speech, may be more resilient against distortions introduced by compression.

We were initially interested in how a better vs. poorer ear interacted with compression effects to affect restoration. Accuracy and restoration effects in the two level conditions were similar across ears. It was difficult to characterize what made an ear “poorer” or “better.” Self-report did not always reflect performance. Six of 12 participants showed a discrepancy between their self-reported “better” ear and the ear with the highest intact speech understanding score. Participants were likely using other criteria than their own perception of their own intact speech understanding ability to decide which ear was “better.” Interestingly, of these six participants, three had very small differences in intact speech scores between ears (1.9 to 3.1%), and three had quite dramatic differences in scores (9.4 to 20.5%), meaning the "misidentification" was not a result of participants having two similarly performing ears.

We hypothesized that a poorer ear would struggle to encode the distortions introduced by compression algorithms, and thus lead to worse performance. This is because a poorer ear was expected to have poorer electrode/nerve interface (Kan, 2018), potentially due to longer durations of non-normal hearing, which could cause auditory neurons to deteriorate in that ear (Fetterman & Domico, 2002). However, seven out of 12 participants in this experiment had fairly symmetrical durations of non-normal hearing across ears (±5 years difference). Furthermore, nine out of 12 participants had fairly symmetrical onsets of non-normal hearing across ears (±5 years difference). If these two factors – duration of non-normal hearing and age at onset of non-normal hearing – are expected to help identify a poorer vs. better ear, our sample was perhaps too symmetric to allow for such a categorization. Future research should attempt to characterize what makes an ear a poorer-performing one, and what metrics CI users use when identifying their poorer vs. better ears. Perhaps some bilateral CI users feel they have symmetric hearing across ears, and thus asking them to identify a poorer ear is leading to a false forced choice.

To summarize, restoration benefits were again not observed among participants with CIs. Contrary to our hypothesis, engaging AGC appeared to improve noise-burst interrupted speech understanding. This finding contradicts previous research in this area, and supports the notion that perhaps the traditional restoration paradigm is not functional with CI users. More favorable SNRs may be required for restoration to work in this population – the opposite of what is needed for NH listeners.

Chapter 4: Experiment 3: Measuring interactions of peripheral auditory encoding and prior linguistic knowledge on restoration

Priming has been shown to strongly enhance the restoration effect (Samuel, 1981). In the present study, we tested if providing a semantic cue – here, a single word meaningfully related to the content of the upcoming sentence – can effectively "prime" a listener for the upcoming sentence and increase restoration. Semantic cues can activate meaningful associations that allow for faster and more efficient processing of upcoming speech (McNamara, 2005). However, semantic cues may enhance restoration differently based on the quality of the bottom-up acoustic information, namely whether that acoustic information is highly degraded. A bilateral CI user may experience differing levels of degradation across their two devices due to having a "better ear" and a "poorer ear" (Kan, 2018). A poorer ear may have experienced less success with a CI, possibly due to poor electrode/nerve interface, and this could be reflected in poorer speech understanding scores. We would expect such an ear to experience high levels of signal degradation. In contrast, less severe signal degradation may occur in an ear with comparatively better electrode/nerve interface (i.e., a "better ear"). Experiencing more signal degradation, specifically, having access to fewer channels of spectral information, has been shown to reduce restoration in NH listeners (Başkent, 2012; Bhargava et al., 2014; Clarke et al., 2016). By testing bilateral CI users, we can measure the extent to which ears contributing potentially different levels of degradation on bottom-up acoustic cues interact with top-down linguistic knowledge, all while holding linguistic skill constant (i.e., utilize a within-subjects design). This integration of top-down knowledge and bottom-up acoustic information is key to understanding speech in noisy environments (Başkent, 2012; Patro & Mendel, 2016; Shinn-Cunningham & Wang, 2008).

We hypothesized that CI users would be able to utilize linguistic knowledge to restore speech with a better ear, but would fail to do so with a poorer ear. This is because greater degradation of the bottom-up acoustic information in the poorer ear would prevent successful integration with top-down knowledge.

4.1 Methods

4.1.1 Participants

Eighteen CI users participated in Experiment 3. Two additional CI users were tested, but were dropped from the analysis due to equipment failure during experiment presentation. Table 6 presents information about tested participants. The mean age of participants was 63.7 years old (SD=13.3 years, range=32 to 81 years). Because this experiment utilized an ear presentation manipulation, information about each ear individually is presented in the table. On average, left ears experienced earlier ages at onset of non-normal hearing (*m*=19.7 years, vs. right ears at *m*=26.9 years) and longer durations of non-normal hearing prior to implantation (*m*=34.1 years, vs. right ears at *m*=28.2 years).

The "better ear" designation was based on performance with ten baseline intact sentence scores presented at 55 dB SPL; for this group, 10 participants had a right "better ear" and eight participants had a left "better ear." These designations often conflicted with patient self-report of which ear was their "better ear": eight participants reported the opposite ear as their "better ear." For some of these participants, ear performance at baseline was quite similar across ears, so it is unsurprising that an opposite ear was reported as the “better ear.” Only three participants with “mismatched” ear designations had comparatively large (i.e., greater than 4%) performance differences between their self-reported better ear and best-performing ear on the baseline test (see participants CAY, CBC, and CBF in Table 6).

Table 6. Demographic information for participants in Experiment 3.

Subject	Age at Testing (years)	Age at onset of non-normal hearing (years)		Duration of non-normal hearing prior to first implantation (years)		"Better Ear" based on Intact Sentence Scores at 55 dB SPL	Intact Sentence Scores Difference between Better/ Poorer Ears at 55 dB SPL (%)	Processing Speed Score (age-uncorrected standard score)	Working Memory Score (age-uncorrected standard score)	Attention Score (age-uncorrected standard score)	PPVT Score (age-corrected standard score)	MoCA Score (out of possible 30 points)
		L	R	L	R							
CAB	74	4.5	4.5	46.5	53.5	Right	6.0	80	82	102	108	27
CAD	79	55	55	8	14	Left	3.2	63	97	96	126	29
CAK	73	35	57	22	12	Right*	3.4	99	78	97	104	26
CAP	49	39	39	1	0	Left*	2.0	122	113	109	96	29
CAQ	61	34	34	23	23	Right*	4.0	105	101	104	109	28
CAS	55	33	33	11	15	Left*	1.9	103	105	94	97	27
CAT	32	10	10	13	8	Left	1.0	122	97	113	93	26
CAY	61	35	32	18	16	Left*	12.7	115	101	106	111	29
CBC	81	6	70	68	6	Right*	38.0	84	105	101	107	28
CBF	61	5	5	47	52	Left*	24.0	99	82	97	99	24
CBH	66	0	0	57	58	Left†	N/A†	99	94	93	91	27
CBR	66	0	0	60	58	Right	14.0	97	94	92	99	27
CCA	79	13	70	60	1	Right‡	N/A‡	74	113	95	134	28
CCO	74	2	2	61	58	Right	45.0	90	105	93	116	24
CDB	60	28	28	13	21	Right	5.0	103	113	104	99	27
CDQ	51	3	3	44	40	Right	2.0	97	97	98	91	27
CDS	77	11	11	56	58	Left*	2.0	84	105	99	126	27
CES	48	41	30	5	14	Right	16.0	124	97	112	101	27
Average	**63.7**	**19.7**	**26.9**	**34.1**	**28.2**	-	**11.3**	**97.8**	**98.8**	**100.3**	**105.9**	**27.1**
St. Dev.	**13.3**	**17.5**	**24.1**	**23.3**	**22.2**	-	**13.5**	**16.8**	**10.4**	**6.5**	**12.6**	**1.4**
Range	**32 - 81**	**0 - 55**	**0 - 70**	**1 - 68**	**0 - 58**	-	**1 - 45**	**63 - 124**	**78 - 113**	**92 - 113**	**91 - 134**	**24 - 29**

*Best-performing ear did not match self-reported "better ear"

†Intact sentence scores were not measured due to experimenter error; self-reported "better ear" information was used instead to classify ears.

‡Second ear was not tested in experiment due to <50% correct intact baseline scores.

In general, baseline scores were similar across ears; only six of 18 participants showed performance differences between ears greater than 10%. On average, right ears had a baseline score of 91.5% (SD=7.8%), and left ears had a baseline score of 86.3% (SD=14.8%), an across-ear difference of 5.2%. When considering better ear vs. poorer ear performance, better ears had an average baseline score of 94.2% (SD=5.7%), and poorer ears had an average baseline score of 83.2% (SD=14.0%), an across-ear difference of 11.7%.

When age at onset of non-normal hearing was considered for better ears vs. poorer ears (rather than left vs. right ears), the average age at onset in a better ear was 27.0 years (SD=24.1, range=0 to 70 years) and in a poorer ear was 19.5 years (SD=17.4, range=0 to 55 years). Thus, better ears tended to experience non-normal hearing at later ages compared to poorer ears. In a similar vein, the average duration of non-normal hearing prior in a better ear was 27.6 years (SD=21.8, range=1 to 58 years) and in a poorer ear was 34.6 years (SD=23.5, range=0 to 68 years). Thus, better ears tended to have shorter durations of non-normal hearing compared to poorer ears.

Processing speed, working memory, attention, and vocabulary scores were generally near standard scores of 100, with the greatest standard deviations observed for processing speed and vocabulary (Table 6). Thus, this group had generally average executive functioning and average vocabulary knowledge. Finally, all participants passed the Montreal Cognitive Assessment (MoCA) with scores of 24 or greater (*m*=27.1), indicating a lack of mild or moderate cognitive impairment (Nasreddine et al., 2005).

4.1.2 Stimuli

Stimuli were 240 IEEE sentences, which are declarative sentences containing 5-12 words (Rothauser et al., 1969). The sentences were recorded by an adult male speaker of Standard American English dialect. The two interruption types (silent gaps, noise bursts) were be applied to sentences in the same manner as described in Experiment 1, such that 120 sentences were interrupted with silent gaps and 120 sentences were interrupted with noise bursts.

A semantic cue (a single word meaningfully related to the content of the sentence about to be presented) was presented visually on a computer monitor prior to each sentence, for 120 sentences (60 of which were silent-gap interrupted, and 60 of which were noise-burst interrupted). Semantic cues were generated in the following way. Three assistants without knowledge of the present experiment were provided a list of the 720 total IEEE sentences, and were asked to generate one to two words for each sentence that were meaningfully related to the sentence content. The answers were compiled and the most commonly reported related word, or the word judged most appropriate by the experimenter, was chosen as that sentence's “semantic cue” word. For example, the word “fish” was chosen for the IEEE sentence “A rod is used to catch pink salmon.” The assistants were instructed that words in the target sentence could not serve as cues, nor could any conjugation of a verb in the target sentence.

One cue word was associated with each of the 720 sentences through this method. To determine which 240 of these sentences had the “best” cue words, to be used in the real experiment, a short pilot study was conducted. Four young NH adults participated in the pilot study, which was conducted using PsychoPy2 (Peirce et al., 2019). Each participant was presented all 720 sentences auditorily over headphones, one at a time in random order. After the presentation of each sentence, a written word appeared on the computer monitor and participants decided via a lexical decision task whether the word was a real word or non-word, using a keyboard press to indicate their choice. Each participant was presented 180 IEEE sentences (one-fourth of the set) followed by the related cue word, 180 sentences followed by an unrelated word (a cue word associated with a different sentence in the set), and 360 sentences followed by a non-word (Rastle, Harrington, & Coltheart, 2002). The target 180 sentences (the ones with the related cue word of interest) were rotated among the four participants; thus, for Participant 1, IEEE sentences 1 through 180 were followed by the related cue word; for Participant 2, IEEE sentences 181 through 360 were followed by the related cue word; and so on. Accuracy and reaction times in the lexical decision task were reviewed following testing.

Accuracy was high, with participants achieving an average of 96.3% correct in their lexical decisions. Reaction times were, on average, 0.539 seconds for related words, 0.550 seconds for unrelated words, and 0.620 seconds for non-words. All reaction time data for related words from all four participants was compiled into a single document, and the 240 sentences with the fastest reaction times (and correct classifications) to the cue words were selected for the main experiment. In this subset, the difference between reaction times for unrelated vs. related words was 0.03 seconds, meaning the related words were identified 0.03 seconds faster on average than unrelated words. A better method to consider for future work in this area would be instead to select the subset of sentences based on the unrelated word reaction time – related word reaction time for the same sentence/word pair, which would directly capture the priming effect. With this method, we could have achieved an unrelated vs. related words difference of 0.16 seconds, had we selected the 240 sentences with the highest values on this measure. As it is, our subset contains words with which the participants likely had the most experience (i.e., words with high frequency in their lexicons). Still, our main manipulation in the main experiment was the presentation of a real word vs. no word at all, so while our real words may not have always been among the strongest primed sentence/word pair from pilot testing, the real word should be high frequency enough to be easily accessible by CI users.

Any one participant in the main experiment was only randomly presented 120 sentences from this set of 240 sentences with related cue words. For another 120 sentences (not duplicates of the first 120), no semantic cue was provided to the participant. Instead, during these trials, a series of X symbols (equal in length to the target sentence's associated semantic cue word) was presented prior to the target sentence. No sentences appeared twice to the same participant as both a cued and uncued sentence. Sentences were randomly assigned to cued vs. uncued conditions for each participant.

4.1.3 Equipment

Participants were seated in a soundproof booth, 1 meter in front of a computer monitor located at eye-level at 0˚. Sentences were presented over a pair of loudspeakers located at ±45˚. A computer keyboard was used for participants to record responses. MATLAB 2018b (Mathworks; Natick, MA) was used to administer the experiment.

To measure linguistic knowledge, participants completed the Peabody Picture Vocabulary Test, Fourth Edition (PPVT-4), which measures receptive vocabulary size (Dunn & Dunn, 2007). Scores from this test were considered a proxy measure of the participant's receptive language ability. Furthermore, participants completed a battery of cognitive tests available via the NIH Toolbox Cognition Battery iPad application (Gershon et al., 2013; Tulsky et al., 2014). For attention and executive functioning, Flanker Inhibitory Control and Attention Test Age 12+ was used; for working memory, List Sorting Working Memory Test Age 7+ was used; for processing speed, Pattern Comparison Processing Speed Test Age 7+ was used. The test battery was administered on an iPad 2 (Apple, Inc.; Cupertino, CA) in a quiet location. The test battery was completed in 15 minutes or less.

4.1.4 Procedure

The design of the experiment was ear presentation (two levels: “better” ear, “poorer” ear), semantic cue (two levels: present, absent), and interruption (two levels: silent gap, speech-shaped noise burst), for a total of eight conditions with 30 sentences per condition.

Before the presentation of each sentence, participants focused on a cross hair presented in the middle of the computer screen. In the semantic cue “present” condition, a word semantically related to the sentence (e.g., “FISH”) replaced the cross hair for two seconds and disappeared. The sentence was then immediately auditorily presented (e.g., “A rod is used to catch pink salmon”). In the semantic cue “absent” condition, a series of X characters (equal in length to the semantic cue word associated with that sentence, e.g., “XXXX”) replaced the cross hair instead. Speech with noise interruptions was presented at –10-dB SNR, with speech presented at 55 dB SPL. Participants were instructed to listen to each sentence and repeat aloud what they heard into a voice recorder. When finished, participants were instructed to press the space bar to begin the next trial. The experiment was self-paced. Two experimenters graded responses separately, one live and one off the voice recording. Experimenters recorded the number of words correct for each sentence. Inter-rater reliability for the full dataset (n=18) was 82.3% based on number of sentences agreed on. Inconsistencies were resolved by averaging the scores of the two graders for that specific trial.

4.2 Results

4.2.1 Multilevel Model Analysis

Prior to running the model, the extent to which any participants showed restoration was inspected by analyzing the mean data for each participant in each of the ear presentation × semantic cue conditions (see Figure 6). Seven participants (out of 18) always performed better with silent-gap interruptions compared to noise-burst interruptions, and thus never showed restoration. Among the remaining participants, three participants showed restoration in the better ear/semantic cue present condition; three participants showed restoration in the better ear/semantic cue absent condition; five participants showed restoration in the poorer ear/semantic cue present condition; and six participants showed restoration in the poorer ear/semantic cue absent condition. Four participants (out of 18) showed restoration in multiple conditions; for example, CBC always showed restoration with the poorer ear, and CCA always showed restoration when a semantic cue was present.

Figure 6. Illustration of which participants showed restoration effects across the various listening conditions.

Participants who show restoration in each condition

Better Ear, Cue	Better Ear, No Cue	Poorer Ear, Cue	Poorer Ear, No Cue
CAP			
CCA		CCA	
CDQ	CDQ		CDQ
	CAS		
	CAK	CAK	CAK
		CBH	
		CES	
		CBC	CBC
			CAB
			CAD
			CDB

No Restoration: CAQ, CAT, CAY, CBF, CBR, CCO, CDS

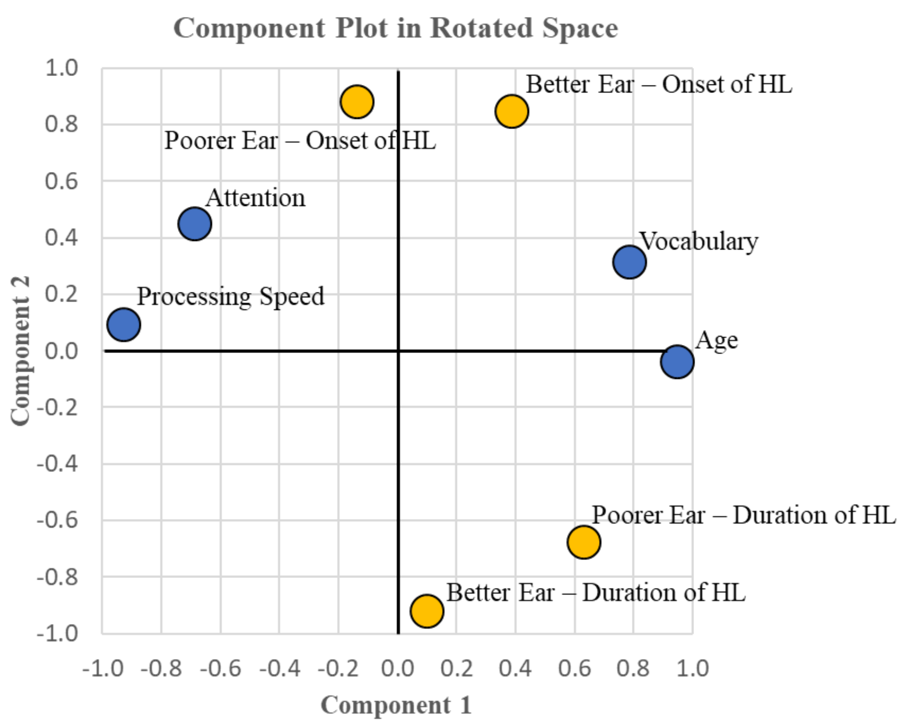
Next, we investigated whether participant variables showed multi-collinearity, which can result in a non-converging multilevel model. Any participant variables exhibiting multi-collinearity could be submitted to a principal component analysis in order to generate uncorrelated composite variables. The variables entered into the Pearson correlation analysis were age, age at onset of non-normal hearing for better and poorer ears, duration of non-normal hearing prior to implantation for better and poorer ears, processing speed, working memory, attention, and vocabulary scores. Age was significantly negatively correlated with processing speed (r=−0.85, p<0.001) and attention (r=−0.64, p=0.005), and was significantly positively correlated with vocabulary (r=0.70, p=0.001) and duration of non-normal hearing in the poorer ear (r=0.63, p=0.005). Thus, older participants typically had poorer cognition, while also having larger vocabularies and longer durations of hearing loss in their poorer ear specifically.

In terms of cognitive measures, processing speed was significantly positively correlated with attention (r=0.66, p=0.003), and significantly negatively correlated with vocabulary (r=−0.68, p=0.002) and duration of non-normal hearing in the poorer ear (r=−0.59, p=0.01). Attention was significantly negatively correlated with duration of non-normal hearing in the poorer ear (r=−0.66, p=0.003). Working memory did not correlate with any other measure.

In terms of hearing history measures, age at onset of non-normal hearing in the better ear was significantly positively correlated with age at onset of non-normal hearing in the poorer ear (r=0.57, p=0.014), and significantly negatively correlated with duration of non-normal hearing in the better ear (r=−0.85, p<0.001). This indicated that participants with later ages of onset of non-normal hearing in one ear were also more likely to have a later age of onset in the other ear; furthermore, a later age at onset was associated with a shorter duration of hearing loss in that ear. This pattern was also observed for age at onset of non-normal hearing in the poorer ear, which was significantly negatively correlated with both the duration of non-normal hearing in the better ear (r=−0.69, p=0.002) and in the poorer ear (r=−0.81, p=<0.001). Duration of non-normal hearing in the better ear was positively correlated with duration of non-normal hearing in the poorer ear (r=0.61, p=0.007).

Principal components analysis was used for compiling these highly correlated participant variables onto components. Using varimax rotation and Kaiser normalization, two components were extracted with Eigenvalues greater than 1 (see Fig. 7). We found that age, processing speed, attention, and vocabulary loaded as a single component (Eigenvalue=3.4, percent of variance=43.0%). That is, older age was associated with slower processing speeds, poorer attention, and larger vocabularies. We found that durations of non-normal hearing in the better and poorer ears, and ages at onset for the better and poorer ears loaded as a second component (Eigenvalue=3.1, percent of variance=38.7%). That is, later onsets of non-normal hearing in the better and poorer ears were associated with shorter durations of non-normal hearing in the better and poorer ears. These two components were included as the participant variables in the multilevel model. A third participant variable, working memory, was also included in the multilevel model. Working memory did not significantly correlate with any other participant variable, and did not primarily load on either of the two principal components outlined above.

Figure 7. Component plot in rotated space of the eight variables entered into the principal components analysis. All variables were entered in standardized, *z*-score form. Blue symbols represent variables loading primarily on Component 1. Yellow symbols represent variables loading primarily on Component 2.



In addition to the participant variables, the following variables were included as fixed factors in a linear multilevel model: semantic cue (absent vs. present; effect-coded as −.5 and +.5, respectively), interruption type (silent gap vs. noise burst; effect-coded as −.5 and +.5, respectively), ear presentation (poorer ear vs. better ear; −.5 and +.5, respectively), and all interactions. The dependent variable was percent words correct per sentence. Model-building followed recommendations outlined in Hox et al. (2018). The final reduced model, presented in Table 7, included the random intercepts of participant (explaining 31% of the variance), ears within participants (explaining 15% of the variance), and sentence (explaining 8% of the variance), as well as the sentence random slope of interruption type (explaining 8% of the variance). Per the residual value, 38% of the variance in results was left unexplained. Figure 8 shows average overall performance of participants across the various conditions, and Figure 9 shows perceptual restoration effects.

Table 7. The best-fitting mixed effects model for Experiment 3. SG = silent gaps. NB = noise bursts.

Fixed Effects	**Estimate**	**SE**	***t***	***p***
Intercept	0.45	0.05	8.74	<0.001*
Semantic cue *(effect coded = −.5 no cue, +.5 cue)*	0.05	0.01	6.81	<0.001*
Interruption type *(effect coded = −.5 SG, +.5 NB)*	−0.06	0.01	−5.68	<0.001*
Ear presentation *(effect coded = −.5 poorer, +.5 better)*	0.09	0.05	1.77	0.095
Component 1 *(Age, Cognition, Vocabulary)*	−0.12	0.05	−2.25	0.036*
Interruption type × Ear presentation	−0.05	0.02	−3.40	<0.001*
Interruption type × Component 1	0.03	0.01	3.73	<0.001*

Random Effects	**Variance**	**SD**
Participant intercept	0.04	0.19
Ear within participant intercept	0.02	0.14
Sentence intercept	0.01	0.11
Interruption type slope (by sentence)	0.01	0.10
Residual	0.05	0.23

Figure 8. Average performance with interrupted speech across ear and cue conditions. Error bars indicate standard error. SG = silent gaps. NB = noise bursts.

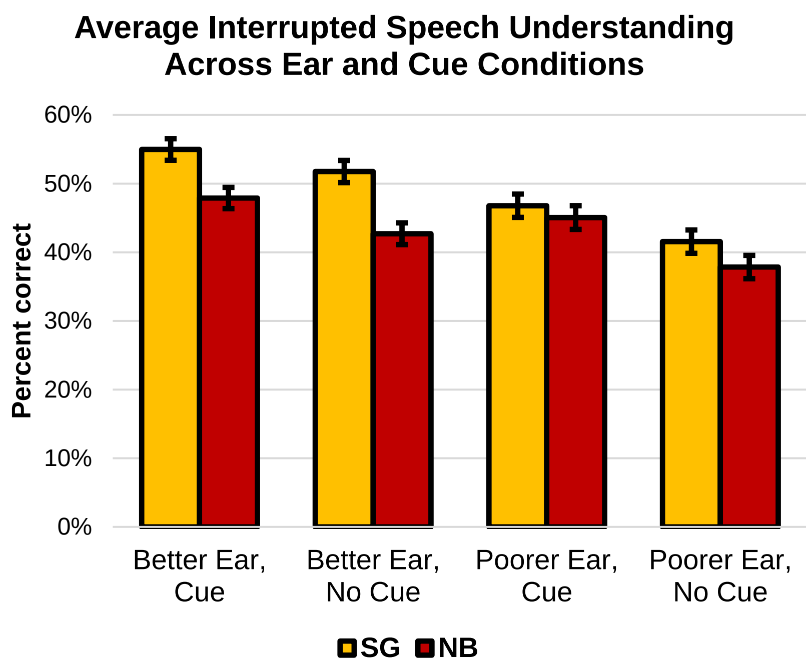
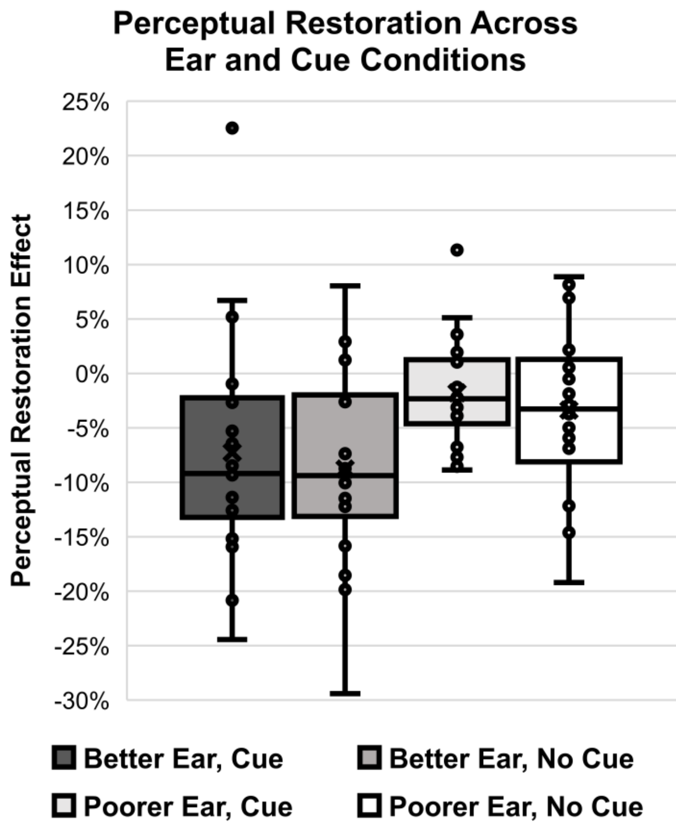
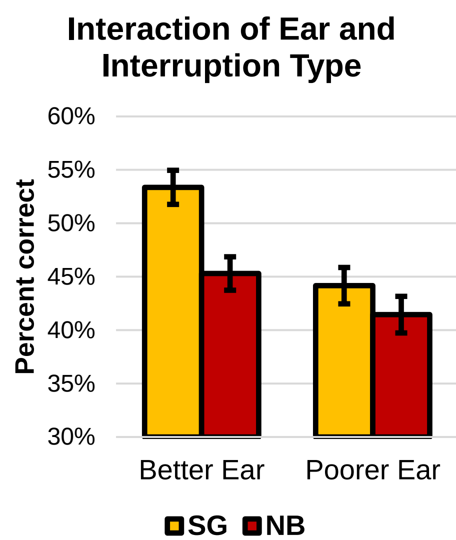


Figure 9. Perceptual restoration effects in Experiment 3, across ear and cue conditions.



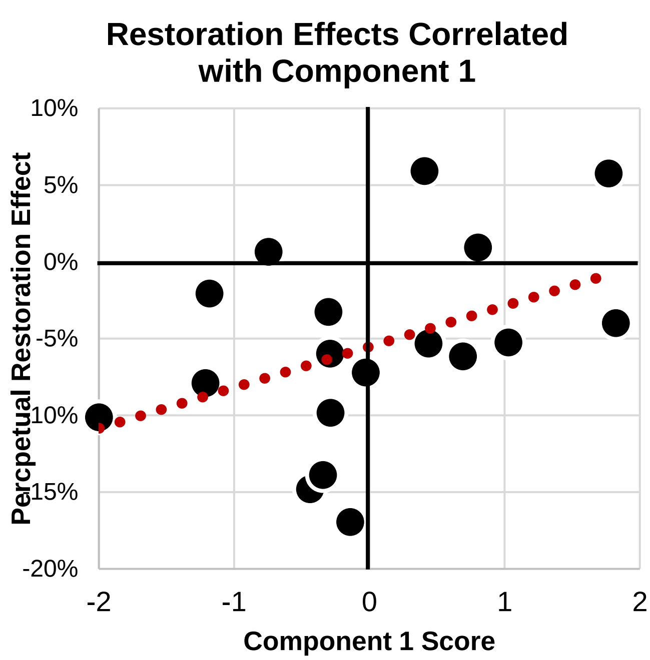
In terms of overall average accuracy, performance with silent gaps was always better than with noise bursts (see Fig. 8; $p<0.001$), and performance with semantic cues present was always better than when semantic cues were absent ($p<0.001$). The effect of ear presentation was not significant ($p=0.095$), but the interaction of interruption type with ear presentation was significant ($p<0.001$). Figure 10 illustrates this interaction. Using the *emmeans* package available in R (R Core Team, Vienna, Austria), we found that the interaction was significant because with silent gaps, the better ear performed significantly better than the poorer ear ($p=0.024$), while with noise bursts, both ears performed similarly ($p=0.22$). This means that the better ear had a particular advantage over the poorer ear in the silent-gap condition, specifically. The better ear achieved 53% accuracy with silent gaps, and the poorer ear achieved 44% – a difference of 9%. In contrast, the better ear achieved 45% with noise bursts, and the poorer ear achieved 41% – a difference of 3%. In both ear conditions, performance with silent gaps was always significantly higher than performance with noise bursts (for better ears, $p<0.001$; for poorer ears, $p=0.014$), demonstrating the lack of a restoration effect in either ear.

Figure 10. Average performance with interrupted speech across ears (collapsed across cue type). The interaction of ear and interruption type was significant, per the mixed effects model. Error bars indicate standard error. SG = silent gaps. NB = noise bursts.



The main effects of working memory and Component 2 were not significant and did not interact with any other variables, and so were removed from the model. The main effect of component 1, associated with age, processing speed, attention, and vocabulary, was significant. As scores on Component 1 increased (meaning participants were older, had slower processing speeds, poorer attention, and larger vocabularies), overall performance significantly decreased (p=0.036). However, as Figure 11 illustrates, Component 1 interacted significantly with interruption type (p<0.001). This indicated that performance with noise bursts improved relative to performance with silent gaps as Component 1 scores increased. Thus, more positive restoration effects were associated with older CI users with poorer cognitive skills and larger vocabularies. While this relationship was significant, very few participants actually experienced a restoration benefit (Fig. 11).

Figure 11. Differences in performance with noise bursts vs. silent gaps (i.e., restoration effects) are plotted against Component 1 scores for each participant. As scores on Component 1 increase, restoration effects become more positive, meaning performance with noise bursts begins to improve relative to performance with silent gaps.



4.2.2 Cluster Analysis

While the multilevel model analysis helped identify several important aspects of the data, it mainly focuses on average results across the participants. As shown previously in Figure 6, several participants in the study did show restoration effects, albeit across several different listening conditions without a clear pattern of results. However, looking only at the multilevel model, one would conclude that no participants on average achieved restoration benefit. Thus, one more analysis was used that considered participant variables and how they affected perceptual restoration ability.

Options for this participant variable analysis included considering comparing participants who experienced non-normal hearing prior to full language development (i.e., “prelingual” participants) to those participants who lost hearing after language development (i.e., “postlingual” participants). Possibly non-normal language development could lead to less stable lexical representations, putting participants with prelingual hearing loss at a disadvantage for perceptual restoration. Another option was comparing participants with symmetric versus asymmetric hearing histories – that is, participants who reported non-normal hearing loss in both ears at the same age, versus participants who reported non-normal hearing loss at different ages for different ears. Possibly continued access to normal hearing in at least one ear would reduce the chance that perceptual restoration ability deteriorates. A third option was comparing participants with asymmetric baseline scores across their better and poorer ears to those with symmetric baseline scores across ears. For example, CAY, CBC, CBF, CBR, CCO, and CES all had greater than 10% differences in performance across their better and poorer ears. These participants were functionally affected by asymmetric hearing, and perhaps this would impact restoration ability in one ear versus the other.

All of these possibilities could be evaluated with a cluster analysis. Cluster analysis is a method of sorting participants into groups based on their scores on variables of interest. Participants in each group are thus more similar to one another on those variables (Pastor, 2010). In the present study, the variables by which participants were classified were the standardized variables of age at testing, processing speed score, attention score, working memory score, vocabulary score, onsets of non-normal hearing in the better and poorer ears, and durations of non-normal hearing in the better and poorer ears (n=9 variables). Standardization of variables prior to cluster analysis is important to prevent different scales from biasing the clustering process. Unfortunately, intact speech scores could not be included in the cluster analysis, as two participants did not have intact speech score data and would have been removed entirely from the analysis (see Table 6).

A hierarchical cluster analysis was conducted using a between-groups linkage method and squared Euclidean distance. Three clusters emerged from the analysis based on inspection of the dendrogram (Fig. 12). Cluster 1 contained seven participants, Cluster 2 contained seven participants, and Cluster 3 contained four participants.

Figure 12. Dendrogram for cluster analysis. The *y*-axis lists participants. The *x*-axis denotes rescaled distances. The three clusters are highlighted in navy, blue, and pale blue.

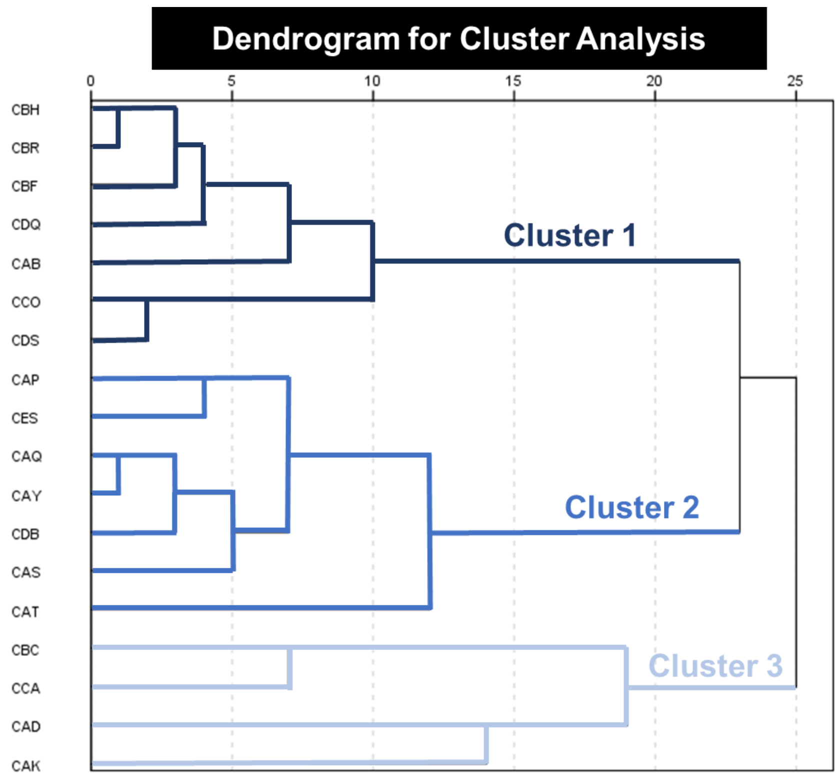


Table 8 presents how each cluster differed from one another on each of the variables entered into the cluster analysis (on the original scales), and also lists the mean scores on each variable for the sample as a whole. Cluster 1 was characterized largely by their hearing histories; this group experienced early, symmetrical onset of non-normal hearing in both ears, and experienced similarly long durations of non-normal hearing. This group was called the "symmetrical group with early onsets/long durations of non-normal hearing." Cluster 2 was characterized by a mixture of age, cognitive abilities, and hearing histories; they were typically younger than the rest of the sample and had better cognitive scores. This group tended to have symmetric hearing histories across ears, experiencing hearing loss in their 30s on average, with ears experiencing about a decade of loss prior to implantation. This group was called the "symmetrical group with late onsets/short durations of non-normal hearing." Cluster 3 was also characterized by a mixture of age, cognitive abilities, and hearing histories; participants in this group were typically the oldest participants in the sample, and had large vocabularies. Their hearing histories were asymmetric, with a late onset and short duration of loss in the better ear. This group was called the "older asymmetrical group."

Table 8. Average scores on each of the variables for each cluster, as well as for the sample as a whole. Standard deviations are listed within parentheses.

	Cluster 1 (*n*=7)	**Cluster 2 (*n*=7)**	**Cluster 3 (*n*=4)**	**Entire Sample (*n*=18)**
Age (years)	**67** (9)	**52** (10)	**78** (3)	**64** (13)
Processing Speed	**92** (8)	**113** (10)	**80** (15)	**98** (17)
Working Memory	**94** (9)	**104** (7)	**98** (15)	**99** (10)
Attention	**96** (4)	**106** (6)	**97** (3)	**100** (7)
Vocabulary	**104** (13)	**101** (7)	**118** (15)	**106** (13)
Better Ear - Age at Onset (years)	**4** (4)	**30** (9)	**63** (8)	**27** (24)
Poorer Ear - Age at Onset (years)	**4** (4)	**31** (10)	**27** (22)	**20** (17)
Better Ear - Duration of Loss (years)	**53** (7)	**14** (7)	**7** (5)	**28** (22)
Poorer Ear - Duration of Loss (years)	**54** (7)	**11** (8)	**41** (27)	**35** (24)

Cluster designation was entered into a mixed effects model also containing the variables of interruption type, semantic cue, and ear presentation. The final reduced model is presented in Table 9. Cluster 1 was used as the referent category in this analysis. As a reminder, Cluster 1 is the "symmetrical group with early onsets/long durations of non-normal hearing." For Cluster 1, average performance overall was 36% words correct;

adding noise bursts decreased performance (*p*<0.001), and adding semantic cues increased performance (*p*<0.001). For Cluster 1 and all other clusters, adding noise bursts to speech presented to the better ear decreased performance further (*p*=0.001). This is the same interaction observed in the previous multilevel model analysis (see Table 7 and Fig. 10).

Cluster 2, the "symmetrical group with late onsets/short durations of non-normal hearing," performed significantly better overall compared to Cluster 1 (*p*=0.038), achieving approximately 61% words correct. This group experienced an even bigger decrease in performance with noise bursts compared to Cluster 1 (*p*=0.01), while the helpful effect of semantic cue on performance was the same across the two groups.

Cluster 3, the "older asymmetrical group" performed overall similarly to Cluster 1, achieving approximately 36% words correct. In contrast to Cluster 1 and Cluster 2, participants in Cluster 3 showed an increase in performance with noise bursts, i.e., a restoration effect (*p*<0.001). This interaction of cluster and interruption type is presented in Figure 13. Cluster 3 also experienced a significant interaction of semantic cue and ear presentation, with the provision of a semantic cue particularly increasing scores in the better ear specifically (*p*=0.02).

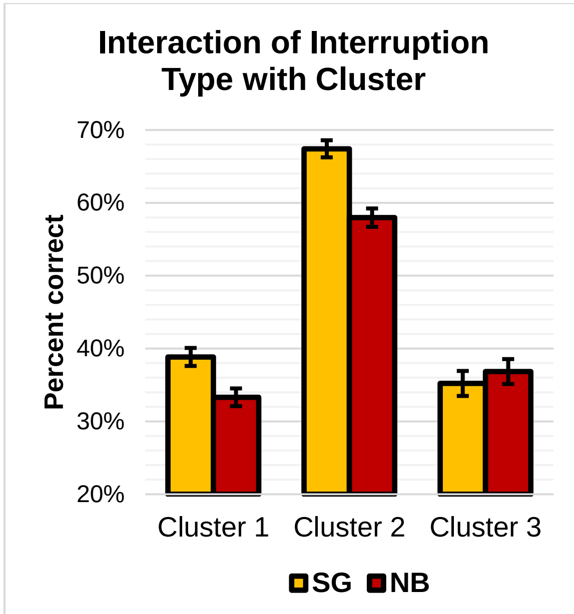
In summary, the main takeaway from this analysis is that Cluster 3 was the only cluster to benefit from a restoration effect. This cluster is characterized by older age, asymmetrical hearing, and strong vocabularies. This restoration effect benefit for Cluster 3 was not impacted by the provision of a semantic cue or ear presentation.

Table 9. Mixed effects model analysis including cluster designation.

Fixed Effects	Estimate	SE	*t*	*p*
Intercept	0.36	0.08	4.65	<0.001*
Cluster 2 *(referent: Cluster 1)*	0.25	0.11	2.24	0.038*
Cluster 3 *(referent: Cluster 1)*	-0.02	0.13	-0.12	0.91
Semantic cue *(Effect coded: −.5 cue absent, +.5 cue present)*	0.04	0.01	3.70	<0.001*
Interruption type *(Effect coded: −.5 silent gap, +.5 noise burst)*	-0.05	0.01	-4.14	<0.001*
Ear presentation *(Effect coded: −.5 poorer, +.5 better)*	0.12	0.07	1.64	0.12
Cluster 2 × Semantic cue	0.01	0.02	0.47	0.64
Cluster 3 × Semantic cue	0.02	0.02	1.04	0.30
Cluster 2 × Interruption type	-0.04	0.02	-2.58	0.01*
Cluster 3 × Interruption type	0.07	0.02	3.48	<0.001*
Cluster 2 × Ear presentation	-0.05	0.11	-0.49	0.63
Cluster 3 × Ear presentation	-0.11	0.13	-0.81	0.43
Semantic cue × Ear presentation	-0.04	0.02	-1.62	0.10
Interruption type × Ear presentation	-0.05	0.02	-3.36	0.001*
Cluster 2 × Semantic cue × Ear presentation	0.02	0.03	0.45	0.66
Cluster 3 × Semantic cue × Ear presentation	0.09	0.04	2.25	0.02*

Random Effects	Variance	SD
Participant (Intercept)	0.03	0.18
Ear within participant (Intercept)	0.02	0.14
Sentence (Intercept)	0.01	0.11
Sentence (Interruption type slope)	0.01	0.10
Residual	0.05	0.23

Figure 13. Performance across interruption types and clusters. Cluster 1 (*n*=7) is the "symmetrical group with early onsets/long durations of non-normal hearing." Cluster 2 (*n*=7) is the "symmetrical group with late onsets/short durations of non-normal hearing." Cluster 3 (*n*=4) is the "older asymmetrical group." SG = silent gap. NB = noise burst.



4.3 Discussion

This experiment analyzed the extent to which different levels of degradation in bottom-up acoustic information affected integration with top-down linguistic knowledge during perceptual restoration in CI users. We hypothesized that "poorer ears," which likely experience greater signal degradation, would fail to restore speech, while "better ears," with less signal degradation, would successfully interact with top-down linguistic knowledge to prompt restoration. We hoped to find a three-way interaction of interruption type, ear presentation, and provision of a semantic cue: performance with noise bursts was expected to be highest (and higher than performance with silent gaps) in the better ear when a semantic cue helped prime the upcoming sentence. Previous research has shown the benefit of priming as a way to prompt restoration in normal-hearing listeners (Samuel, 1981); it was unknown if a similar benefit occurred among CI users.

Unlike in Experiments 1 and 2, some participants in the present study showed restoration benefits (see Fig. 9). While 39% of participants did not show restoration in any ear presentation/semantic cue condition, 39% of participants showed restoration in one of the conditions, 11% of participants showed restoration in two of the conditions, and another 11% showed restoration in three of the conditions. Despite this promising individual data, no average restoration benefits were apparent (see Figs. 8 and 9). This lack of an average restoration benefit among CI users was confirmed by the multilevel model analysis (Table 7) – the hypothesized three-way interaction was not significant, and no improvements with noise-burst interrupted speech over silent-gap interrupted speech were observed. Performance with noise-burst interrupted speech was always significantly poorer than performance with silent-gap interrupted speech, on average.

What we found, instead, was an overall helpful effect of semantic cue for repairing interrupted speech in general – whether those interruptions were silent gaps or noise bursts. Thus, top-down linguistic knowledge appears to be utilized by CI users whenever interrupted speech is encountered. We also found that noise bursts were particularly harmful when presented to the better ear (Fig. 10), whether semantic cues were present or absent. We predicted that restoration would be more likely in the better ear, as bottom-up acoustic cues were expected to be higher in quality. High-quality bottom-up cues have been purported to be important for successful speech repair (Başkent, 2012; Bhargava et al., 2014; Jaekel et al., 2018) and stimulating context usage (Patro & Mendel, 2016). Instead, the better ear reacted to noise bursts as interferers rather than prompters of restoration, while silent-gap interrupted speech improved significantly. Perhaps the high-quality encoding of speech information was what was most useful to CI users in the better ear, since when this interrupted but high-quality speech information was presented alone (silent-gap condition), speech understanding increased. Finally, our model showed that the impact of noise bursts on speech understanding were less pronounced if participants were older, had stronger vocabularies, and poorer cognition (see Fig. 11). While this decrease in noise-burst interference was not pronounced enough to elicit restoration (i.e., noise-burst performance was still lower than performance with silent gaps), this finding does align with previous work in the area showing that older listeners, and people with stronger vocabularies, are more likely to repair noise-burst interrupted speech (Benard et al., 2014; Jaekel et al., 2018; Nagaraj & Magimairaj, 2017; Saija et al., 2014).

While the multilevel model did not reveal any significant restoration effects for CI users on average, some CI users appeared to be experiencing restoration (Fig. 9). To detect whether certain groups of CI users, based on their personal characteristics like age, vocabulary, cognition, and hearing histories, could achieve restoration, we conducted a cluster analysis. Three clusters of CI users emerged (Table 8, Fig. 12). Participants in Cluster 1 typically had symmetrical hearing histories across their ears, with early onsets of non-normal hearing and long durations of non-normal hearing. Such hearing histories are usually associated with poorer speech perception outcomes, with longer durations of deafness being correlated with poorer speech understanding in quiet (Blamey et al., 2013; Green et al., 2007) and in noise (Fetterman & Domico, 2002), likely due to anatomical and physiological changes to the auditory system. Prelingual hearing loss, meaning experiencing non-normal hearing before the age of three, is also associated with poorer speech recognition, potentially due its impacts on spoken language acquisition and reorganization of the auditory cortex (Boisvert, McMahon, Dowell, & Lyxell, 2015; Petersen, Gjedde, Wallentin, & Vuust, 2013; Peterson, Pisoni, & Miyamoto, 2010). Cluster 1 showed no restoration, confirmed with a second multilevel model (see Fig. 13 and Table 9).

Participants in Cluster 2 also typically had symmetrical hearing histories across their ears, but instead had late onsets of non-normal hearing and short durations of non-normal hearing. Despite likely being less affected by anatomical/physiological changes to the auditory system caused by long durations of hearing loss, and thus likely having more similar auditory system organization to NH listeners, this group was the most negatively affected by noise-burst interruptions. They showed the strongest noise interference effect (see Fig. 13).

Participants in Cluster 3 had asymmetrical hearing histories and were typically older. This cluster was the only group to show a restoration benefit (Fig. 13). Furthermore, participants in this cluster showed semantic cue and ear presentation effects: interrupted speech performance (in general) was higher in the better ear when semantic cues were available (Table 9). While we did not observe the predicted interaction of interruption type, semantic cue, and ear presentation in this cluster, it was encouraging to find that priming and less-degraded bottom-up acoustic information may boost interrupted speech understanding in general. Having a group of CI users that had asymmetrical hearing histories likely increased the chances that we could observe ear presentation effects, via the designation of a poorer and better ear that more likely appreciably differed in degradation levels (Kan, 2018).

To summarize, CI users on average showed an interference effect rather than a restoration benefit when speech was interrupted with noise bursts. This finding goes against previous literature (Bhargava et al., 2014) but aligns with findings in Experiments 1 and 2. A closer analysis of the results from the current study revealed that some CI users were able to restore speech, but there were no clear patterns for which ear presentation/semantic cue conditions were most likely to prompt restoration.

When CI users were categorized into sub-groups based on their hearing histories and other variables, we found that older CI users with asymmetric hearing histories were most able to restore speech. Previous work has shown that older age is associated with greater restoration benefits, as older listeners tend to use context more while processing speech (Pichora-Fuller, 2008; Sheldon et al., 2008), increasing top-down contributions to noise-burst interrupted sentence understanding (Jaekel et al., 2018; Saija et al., 2014). This group was also most able to utilize semantic information and a better ear to process interrupted in speech in general (i.e., both silent-gap and noise-burst interrupted speech). Our original hypothesis posited that the use of semantic information and a better ear would particularly boost performance with noise bursts, prompting restoration; this was not the case. Restoration in this group was not tied to the presence of a semantic prime or ear used to complete the task. There appears to be a disassociation between gleaning restoration benefit vs. processing interrupted speech in this group of CI users. The latter is directly affected by access to high-quality bottom-up acoustic signals and the opportunity to apply top-down linguistic knowledge. The former, restoration, is unaffected by variables that impact the on-line processing of speech, and instead is more affected by qualities of the participant him- or herself, like hearing history and age. This group had, on average, the latest better ear onset of non-normal hearing (63 years) and the shortest better ear duration of non-normal hearing (7 years). Thus, this group had the longest experience with normal hearing in at least one ear, and therefore likely had the most experience with utilizing restoration as a tactic to repair speech. Future work should recruit more CI users with these qualities (only four CI users in our study fit this profile) and confirm that restoration ability in adult CI users may depend on experience with restoration with normal hearing. It would also be of interest to conduct cluster analyses on larger samples of CI users to determine whether the listener profiles found in our analysis exist in the CI user population at large. Listener profiles could be used to predict speech understanding outcomes and/or inform expectations for CI candidates.

While some individual CI users may be able to restore speech, restoration still appears to be elusive for CI users as a group. The individual CI users who could restore speech in Experiment 3, and who participated in the other experiments in this project, failed to demonstrate restoration in Experiments 1 and 2. Thus, even CI users who can restore in some cases fail to do so all the time. Overall, it appears that manipulations in noise-reduction algorithm availability (Experiment 1), compression engagement (Experiment 2), ear presentation (Experiments 2 and 3), and semantic cue availability generally fail to elicit restoration in CI users. When restoration was observed, it was not consistent within listeners or across speech materials. CI users are more successful at understanding silent-gap interrupted rather than noise-burst interrupted sentences, and show no strong evidence of performing speech repair.

Chapter 5: Experiment 4: Replicating previous work with CI users and perceptual restoration

Following several failures to find consistent restoration in CI users in Experiments 1-3, we next attempted to replicate the original, and only, restoration study performed in CI users to date, which was conducted by Bhargava et al. (2014). In addition to testing the parameters used in that original study, we tested additional duty cycles and interruption rates to get a better sense of how these factors influence restoration in CI users.

The authors of the original study were interested in measuring whether CI users' difficulties with speech understanding in noisy environments were due to reduced restoration ability, with this reduction being caused by how CI processing affects bottom-up acoustic cues. The authors tested restoration in not only CI users, but also in NH listeners and NH listeners presented vocoded speech. The main findings were that under only certain conditions could CI users utilize restoration, and that the loss of restoration ability in other conditions was likely due to CI processing transmitting degraded bottom-up cues. The latter was concluded because when NH listeners were presented vocoded speech, which simulates aspects of CI processing, they struggled to show any restoration. Another finding from the study was that there was considerable variation in restoration benefit across the CI users tested. In a more difficult condition (i.e., when less speech information was provided between interruptions), restoration benefits ranged from −10 to +20 RAUs in CI users, with negative values indicating that noise-burst interrupted speech created interference rather than a benefit. In this case, six of 13 CI users (46%) showed an interference effect rather than a benefit. In the easier condition (i.e., when more speech information was provided between interruptions), restoration benefits ranged from −5 to approximately +20 RAUs in CI users, with only two of the 13 CI users (15%) showing interference effects. The authors concluded that the determination of who showed a positive restoration benefit was driven by intact, non-interrupted sentence understanding scores in quiet, in that higher sentence understanding scores were associated with positive restoration benefits, at least in the more difficult listening condition. Reasons for this included that higher-performing CI users may be able to make better use of speech information and/or may be more sensitive to acoustic speech cues in general.

We had several goals for the present replication study. First, we aimed to replicate the methods used in the Bhargava study as closely as possible in order to measure restoration in CI users. Second, we aimed to vary specific parameters used in the Bhargava study to see whether they influenced restoration and could explain the differences in results between the original study and our Experiments 1-3. Third, we aimed to measure whether intact speech understanding scores were positively correlated with restoration benefits.

5.1 Methods

5.1.1 Participants

We recruited the same number of participants used in the original Bhargava study, *n*=13. Table 10, modified from Bhargava's study, describes their participants. Per the Bhargava paper, "N/A" for the column "Age at onset of hearing loss (years)" indicates that "readings were not available in the patient record."

Table 10. Participant information table adapted from Bhargava et al. (2014) describing the participants in their perceptual restoration study. AB = Advanced Bionics.

Participant	Gender	Age at Testing (years)	Age at onset of hearing loss (years)	CI Brand	Intact Speech Scores (in RAUs)	CVC Phoneme Score %
CI 1	F	28	N/A	Cochlear	102.3	75
CI 2	M	38	3	Cochlear	99.8	85
CI 3	F	22	N/A	Cochlear	88.2	94
CI 4	M	23	N/A	Cochlear	93.0	82
CI 5	F	65	30	Cochlear	117.8	94
CI 6	M	52	33	Cochlear	96.4	95
CI 7	M	65	61	Cochlear	93.5	80
CI 8	F	62	45	Cochlear	98.0	80
CI 9	M	64	N/A	Cochlear	95.6	85
CI 10	F	57	N/A	Cochlear	104.4	85
CI 11	F	65	N/A	Cochlear	81.1	91
CI 12	M	35	1	Cochlear	117.8	90
CI 13	M	55	0	AB	78.4	67
Average		**48.5**	**24.7**		**97.4**	**84.8**
St. Dev.		**16.9**	**24**		**11.8**	**9.2**
Range		**22 - 65**	**0 - 61**		**78.4 – 117.8**	**67 – 95**

The next table (Table 11) details the participant variables for our replication study. On average, compared to the original study, the current study had older participants (average age of 60.4 years compared to 48.5 years), with lower baseline, intact sentence understanding scores (average of 83.2 RAUs compared to 97.4 RAUs) and lower CNC phoneme scores (average of 80.9% compared to 84.8%). It is unclear whether our sample had earlier ages of onsets of hearing loss (average onset of 12.3 years compared to 24.7 years), because onsets were reported for only seven of 13 participants in the original study. It is also unclear how the Bhargava study measured age at onset of hearing loss; the values in Table 11 indicate the earliest age at which non-normal hearing was noticed in at least one of the two ears.

Note that the participants in the Bhargava study spoke Dutch as their native language and completed the study in Dutch. In contrast, our participants used English as their native language and completed the study in English.

Table 11. Participant information from our replication study. AB = Advanced Bionics.

Participant	Gender	Age at testing (years)	Age at onset of non-normal hearing (years)	CI Brand	Intact Speech Scores (in RAUs)	CNC Word Score (%)	CNC Phoneme Score (%)
CAD	M	79	55	Cochlear	111.4	86	95
CAF	F	72	3	Cochlear	80.6	56	74
CAQ	F	61	34	Cochlear	84.7	60	76
CBH	F	66	0	Cochlear	64.8	68	86
CBR	F	66	0	Cochlear	83.2	54	75
CCA	M	79	13	Cochlear	71.9	64	81
CCO	F	74	2	Cochlear	107.2	82	92
CCR	F	70	2	Cochlear	84.5	64	82
CCS	M	43	1	Cochlear	77.2	54	77
CDQ	F	51	3	Cochlear	97.5	64	82
CEI	F	31	1.33	Cochlear	76.8	76	86
CEN	F	45	12	AB	41.0	24	51
CES	M	48	30	Cochlear	101.1	86	95
Average		**60.4**	**12.0**		**83.2**	**64.5**	**80.9**
St. Dev.		**15.3**	**17.2**		**18.8**	**16.7**	**11.5**
Range		**31 - 79**	**0 - 55**		**41.0 - 111.4**	**24 – 86**	**51 - 95**

5.1.2 Stimuli

The original study used sentences from the Vrij University (VU) corpus (Versfeld et al., 2000), which were meaningful Dutch sentences. An example of one of the sentences is (translated into English) “Outside it is dark and cold.” The original study drew from 38 lists produced by a male talker, with each list containing 13 sentences, for an average of 80 words per list. One list was used for familiarization purposes, two lists were used for measuring the baseline intact sentence understanding scores, and 20 lists were used for measuring each of the ten conditions (described below), with 2 lists randomized to each condition.

Our study used sentences from the IEEE corpus (Rothauser et al., 1969). An example of one of the sentences is “The birch canoe slid on the smooth planks.” The sentences were recorded by a male talker, and each list contained 10 sentences. Somewhat similar to the original study, we used one list for familiarization purposes, two lists for measuring baseline intact sentence understanding scores, and 24 lists for measuring each of the twelve conditions (described below), with 2 lists randomized to each condition.

The authors of the original study processed their sentences in the following way. Two interruption types were applied to the sentences: silent-gap interruptions and noise-burst interruptions. Both interruption types were periodic square waves, with an interruption rate of 1.5 Hz and raised 5-ms cosine ramps. The duty cycle was 50% or 75%. For the 50% duty cycle condition, 333 ms of speech was available in every 666 ms-long speech segment. For the 75% duty cycle condition, 500 ms of speech was available in every 666 ms-long speech segment. The SNR of noise-burst interruptions was varied as well: restoration was measured at −10, −5, 0, and 5 dB SNRs. Thus, the ten tested conditions were: (1) silent-gap interruptions with a 50% duty cycle, (2) silent-gap interruptions with a 75% duty cycle, (3-6) noise-burst interruptions with a 50% duty cycle at −10, −5, 0, and 5 dB SNRs, and (7-10) noise-burst interruptions with a 75% duty cycle at −10, −5, 0, and 5 dB SNRs. Speech was always presented at 60 dB SPL.

For the replication study, we tested two interruption types, silent gaps and noise bursts, in order to measure the restoration effect. We additionally tested two interruption rates, 1.5 Hz (used in the original study), and 5 Hz (used in Experiments 1-3), and three duty cycles, 65%, 75% (used in the original study), and 85% (similar to the 80% duty cycle used in Experiments 1-3). All combinations of these parameters were tested, resulting in 12 total conditions (two interruption types × two interruption rates × three duty cycles). Each condition was tested twice, each time with a new sentence list of 10 sentences. Thus, the experiment was composed of 240 sentence trials. Order of conditions was randomized, and sentence list allocation to conditions was randomized. For our experiment, the SNR was fixed at –5 dB; in the original study, no effect of SNR was found in CI users, so we did not choose to vary this factor. We presented speech at the same intensity level as the Bhargava study.

5.1.3 Procedure

In the original study, participants sat in a soundbooth in front of a computer monitor and loudspeaker located at 0 degrees. Participants first completed the baseline speech understanding conditions, then familiarization, then the experiment. Familiarization consisted of participants being presented sentences that were processed with a different interruption rate, duty cycle, and SNR than those used in the main experiment. Participants listened to each sentence during familiarization and repeated aloud what was heard. Feedback during familiarization was an auditory presentation of the intact sentence and a visual display of the text of the sentence. Following completion of familiarization, the main experiment began.

In our replication study, participants sat in a soundbooth in front of a pair of loudspeakers located at ±45 degrees. The computer screen faced the experimenter, who controlled the experiment and was in the soundbooth with the participant for the duration of the experiment. Participants were tested on baseline sentences, then familiarized with the stimuli, then completed the main experiment. Familiarization consisted of presenting participants with stimuli that were processed slightly differently from stimuli in the main experiment: stimuli were presented with a 1.5-Hz interruption rate (used in the main experiment) and 80% duty cycle (not used in the main experiment) at −10-dB SNR (not used in the main experiment). The procedure and feedback for familiarization were identical to those used in the original study.

In the original study, participants were scored on the number of words they correctly reported per list. The percent-correct scores were converted into RAUs. No feedback was provided to participants, and incorrect/absent scores were not penalized. In the replication study, sentences were graded for number of words correctly reported, using lax grading that accepted as correct some changes in tense ("shop" for "shopped" but not "went" for "go") and changes in plurality ("cats" for "cat" or "cup" for "cups"), in line with previous research practices (Jaekel et al., 2018). Similar to the original study, we transformed percent-correct scores into RAUs, no feedback was provided, and incorrect answers were not penalized.

5.2 Results

Prior to describing our own results from the replication study, we describe results from the original study by Bhargava et al. (2014). In the most difficult listening condition (50% duty cycle), CI users showed no restoration effects at any SNR; that is, performance with noise-burst interrupted speech was never significantly higher (or lower) than performance with silent-gap interrupted speech. In the less difficult listening condition (75% duty cycle), CI users showed significant restoration effects at every SNR; that is, performance with noise-burst interrupted speech was significantly higher than performance with silent-gap interrupted speech, indicating a restoration benefit. When examining how participant variables might explain these results, the original study plotted restoration benefits against baseline speech scores. Higher baseline scores were associated with more positive restoration benefits in the 50% duty cycle condition (reported as $r = 0.71$, $p < 0.05$), while there was no relationship in the 75% duty cycle condition (reported as $r = 0.13$, $p = 0.67$). In summary, we should expect to observe a restoration effect in our replicating condition (interruption rate = 1.5 Hz, duty cycle = 75%, and SNR = −5 dB). In this condition, Bhargava and colleagues (2014) found an approximate +5.6 RAU benefit for restoration, or approximately a benefit of 8.8%. Furthermore, we can expect that performance in this condition may not correlate with baseline speech understanding scores, but that performance in decidedly more difficult conditions (e.g., the 65% duty cycle conditions) may correlate positively with baseline speech understanding scores.

Our findings are described below. First, we compare our replicating condition with that in the original study, and then discuss results from the other test conditions. Compared to the +5.6 RAU benefit for restoration in the 1.5-Hz interruption rate, 75% duty cycle, −5-

dB SNR condition found by Bhargava and colleagues, we found a −0.9 RAU interference effect (SE = 3.6, range = −18.9 to +19.7). Seven participants showed restoration on average (+3.6, +3.6, +3.8, +4.3, +10.2, +17.4, +19.7 RAUs). Six participants showed interference (−18.9, −17.9, −16.7, −13.6, −4.2, −3.1 RAUs). Thus, we were unable to find similar average restoration effects to the Bhargava study with the same parameters and largely identical procedures. In terms of accuracy in the replicating condition, the original study showed approximately 50 RAUs correct for the silent-gap interrupted condition, and approximately 55 RAUs correct for the noise-burst interrupted condition. In contrast, our average RAUs correct in the replicating condition for silent-gap interrupted speech was 45.2, and our average RAUs correct for noise-burst interrupted speech was 44.2, both lower than that observed in the original study. Performance in these two conditions in our study was not statistically significantly different, per a paired-samples *t* test: $t(12) = 0.26$, $p=0.802$.

Perhaps a certain level of performance with silent-gap interruptions is necessary to achieve restoration benefits; because our sample's silent-gap interrupted speech understanding was lower than that seen in the original study's, we did not see restoration benefits. However, a closer analysis of the individual data did not confirm this notion—in the replicating condition, the range of performance with silent-gap interrupted speech was similar for participants who achieved a restoration benefit (18 to 72 RAUs) and for those who experienced interference (22 to 78 RAUs).

Average restoration benefits and accuracy in RAUs for all of our study conditions are reported in Table 12. Restoration benefits were observed in two of the six conditions tested: the 1.5-Hz interruption rate with a 65% duty cycle and the 5-Hz interruption rate with an 85% duty cycle. The highest accuracy was in the 5-Hz interruption rate with an 85% duty cycle, and the lowest accuracy was in the 5-Hz interruption rate with a 65% duty cycle. The eight “prelingual” participants – that is, participants who experienced non-normal hearing in at least one ear at $\leq$ 3 years of age, before language development – showed the most restoration benefit, with an average of +3.2 RAUs restoration effect across conditions. The five “postlingual” participants – those who experienced non-normal hearing after completing language development – showed the most interference, with an average of −6.5 RAUs restoration effect across conditions.

Table 12. Average restoration benefits and accuracy in RAUs for our replication study. The replicating condition is underlined. SG = silent gaps. NB = noise bursts.

Condition	Average Restoration Benefit (RAUs)	SE	Range
1.5-Hz interruption rate, 65% duty cycle *(433.3 ms of speech per 666.6-ms segment)*	2.4	2.8	−11.6 to 17.7
<u>1.5-Hz interruption rate, 75% duty cycle</u> *(499.9 ms of speech per 666.6-ms segment)*	<u>−0.9</u>	<u>3.6</u>	<u>−18.9 to 19.7</u>
1.5-Hz interruption rate, 85% duty cycle *(566.6 ms of speech per 666.6-ms segment)*	−1.0	3.0	−24.9 to 14.9
5-Hz interruption rate, 65% duty cycle *(130 ms of speech per 200-ms segment)*	−4.3	3.2	−24.9 to 13.7
5-Hz interruption rate, 75% duty cycle *(150 ms of speech per 200-ms segment)*	2.6	3.1	−13.6 to 20.1
5-Hz interruption rate, 85% duty cycle *(170 ms of speech per 200-ms segment)*	−2.1	3.4	−21.8 to 12.1

Condition	Accuracy (RAUs)	SE	Range
1.5-Hz interruption rate, 65% duty cycle, SG	26.0	4.6	4.2 to 56.9
1.5-Hz interruption rate, 65% duty cycle, NB	28.4	5.6	−2.8 to 68.8
<u>1.5-Hz interruption rate, 75% duty cycle, SG</u>	<u>45.1</u>	<u>5.6</u>	<u>18.0 to 78.1</u>
<u>1.5-Hz interruption rate, 75% duty cycle, NB</u>	<u>44.2</u>	<u>7.6</u>	<u>4.8 to 91.5</u>
1.5-Hz interruption rate, 85% duty cycle, SG	63.4	6.4	39.3 to 100.3
1.5-Hz interruption rate, 85% duty cycle, NB	62.4	7.5	14.4 to 103.5
5-Hz interruption rate, 65% duty cycle, SG	29.3	7.2	−8.1 to 66.3
5-Hz interruption rate, 65% duty cycle, NB	24.9	7.9	−13.0 to 71.2
5-Hz interruption rate, 75% duty cycle, SG	42.9	8.4	−2.4 to 96.8
5-Hz interruption rate, 75% duty cycle, NB	45.5	8.3	5.6 to 83.2
5-Hz interruption rate, 85% duty cycle, SG	64.4	7.8	16.9 to 105.4
5-Hz interruption rate, 85% duty cycle, NB	62.3	7.7	19.4 to 108.4

We analyzed accuracy using a repeated measures ANOVA. Unfortunately, we could not repeat the original study's statistical analysis with our own data (Dunnett's test for multiple comparisons). Bhargava et al. (2014) used the technique to compare several noise-burst conditions to a single silent-gap condition, whereas each of our noise-burst conditions had a partner silent-gap condition against which it could be compared.

The variables of interruption type (two levels, noise-burst and silent-gap interruptions), interruption rate (two levels, 1.5 Hz and 5 Hz), and duty cycle (three levels, 65%, 75%, and 85%) were entered as the independent variables to a RM ANOVA. The dependent variable was accuracy in RAUs. No variables violated Mauchly's Test of Sphericity, so sphericity was assumed and no corrections were used.

The only significant main effect was duty cycle, $F(2,24)=156.8$, $p<0.001$, $\eta_p^2=0.93$. The main effect of interruption type was not significant, $F(1,12)=0.08$, $p=0.78$, $\eta_p^2=0.01$, nor was the main effect of interruption rate, $F(1,12)<0.001$, $p=0.99$, $\eta_p^2<0.001$. No interactions were significant: interruption type × interruption rate, $F(1,12)=0.44$, $p=0.52$, $\eta_p^2=0.04$; interruption type × duty cycle, $F(2,24)=0.36$, $p=0.70$, $\eta_p^2=0.03$; interruption rate × duty cycle, $F(2,24)=0.04$, p=0.96, $\eta_p^2=0.003$; three way interaction, $F(2,24)=1.76$, $p=0.19$, $\eta_p^2=0.13$.

For the main effect of duty cycle, post-hoc paired-samples *t*-tests Bonferroni-corrected for multiple comparisons revealed that performance in every duty cycle was significantly different from every other (all p's <0.001). The best performance was in the 85% duty cycle, followed by the 75% duty cycle, followed by the 65% duty cycle.

To conclude, interruption type did not affect accuracy: similar scores were obtained with silent-gap interrupted sentences and noise-burst interrupted sentences. Thus, we could not confirm the presence of a restoration effect. Because no interactions with interruption type were significant, no combination of parameters (duty cycles and interruption rates) explained interrupted speech understanding. Interruption rate did not affect accuracy either;

similar scores were obtained regardless of how frequent interruptions appeared (i.e., every 666.6 ms vs. every 200 ms). In contrast, longer duty cycles, that is, greater access to speech information across segments, did lead to significantly improved performance. The original study found a similar effect, in that performance was greater in the 75% duty cycle condition compared to the 50% duty cycle condition. Thus, restoration, defined as a significant difference between silent-gap and noise-burst conditions, was not observed via this analysis.

5.2.1 Baseline speech understanding and its correlation with restoration benefits

This analysis matches one used in the original study, which correlated restoration benefits in each duty cycle condition (in RAUs) with baseline sentence understanding scores (in RAUs). We correlated baseline sentence understanding scores (in RAUs) with restoration benefits in each duty cycle × interruption rate condition (in RAUs), for a total of six correlation analyses. The results are presented in Table 13. No significant correlations were found in any of the conditions tested.

Table 13. Pearson correlations between restoration benefits at each interruption rate × duty cycle combination with baseline speech understanding scores. No correlations were significant.

	1.5 Hz, 65% duty cycle	**1.5 Hz, 75% duty cycle**	**1.5 Hz, 85% duty cycle**	**5 Hz, 65% duty cycle**	**5 Hz, 75% duty cycle**	**5 Hz, 85% duty cycle**
r (n=13)	0.31	0.36	0.49	0.12	0.15	−0.10
p	0.30	0.23	0.09	0.70	0.63	0.75

5.2.2 Are the IEEE sentences "restorable"?

One possibility is that our IEEE sentences, unlike the VU sentences utilized in the original study, are not restorable at the parameters tested, even for NH listeners. This could explain why we did not see consistent restoration across conditions and especially why we did not replicate restoration in the replicating condition. To explore this, we tested one NH adult listener (age = 53 years) with the same stimuli processed by a 32-channel noise vocoder. Pilot testing revealed that unprocessed versions of the stimuli presented to separate NH listeners resulted in ceiling performance that reflected no restoration benefits (this issue was also observed in the original Bhargava study, for their NH unprocessed condition). A vocoder can mimic aspects of CI processing, degrading the stimuli enough to bring performance down from the ceiling. The decision to utilize 32 channels was based on findings from Jaekel et al. (2018); while 32 channels is higher spectral resolution than one would expect in real CI users (Berg et al., 2019; Croghan et al., 2017; Friesen et al., 2001), it allows NH listeners to complete restoration tasks with vocoded stimuli without experiencing floor effects.

Our NH adult listener showed high performance on average across conditions (87.3 RAUs). The worst performance, 60.4 RAUs, was observed with silent gaps in the 1.5-Hz interruption rate, 65% duty cycle condition. The best performance, 106.9 RAUs, was observed with noise bursts in the 5-Hz interruption rate, 85% duty cycle condition. Perceptual restoration was observed at every interruption rate × duty cycle combination, with an average restoration benefit of +6.8 RAUs (ranging from +1.4 to +17.2 RAUs). The greatest amount of restoration, +17.2 RAUs, was observed in the 5-Hz interruption rate, 85% duty cycle condition (the condition most similar to the parameters used in

Experiments 1-3). At the replicating condition (1.5-Hz interruption rate, 75% duty cycle), a restoration benefit of +6.2 RAUs was observed.

Thus, it appears that the IEEE sentences used in our replicating study were restorable across conditions. Note that this NH participant was not tested as a direct comparison to our CI user participants, but as a way to determine whether our sentences were restorable. The 32-channel noise vocoder used provides higher spectral resolution than a CI user could be expected to receive, and does not fully capture the listening experiences of CI users.

5.3 Discussion

Experiment 4 had three goals: (1) replicate the original CI restoration study by Bhargava et al. (2014); (2) vary parameters that could impact restoration and assess their effects; and (3) measure whether intact speech understanding scores correlated with restoration benefits, which was a finding in the original paper. One additional goal was also pursued: measuring whether the sentence materials we used were "restorable" by presenting them to a NH listener.

The study by Bhargava et al. (2014) found a +5.6 RAU (approximately 8.8%) restoration benefit in the replicating condition. In contrast, we found a −0.9 RAU (approximately −0.5%) restoration effect in this condition. While the participants in the original study found the noise-burst interruptions helpful for understanding speech in this condition, our participants, on average, did not show this benefit, with seven participants showing positive restoration and six participants showing negative restoration effects. Analyzed statistically, no significant difference in performance in this replicating condition for the silent-gap versus the noise-burst interrupted sentences was observed. Thus, we were unable to confirm the findings reported by Bhargava et al. (2014) – CI users showed no restoration benefits, on average, in this condition. This finding aligns with findings from Experiments 1-3, where participants similarly showed no advantage for noise-burst interruptions and instead tended to show an advantage for silent-gap interruptions, the opposite of the restoration effect.

The second goal of our study was to measure how varying the parameters of duty cycle and interruption rate affected restoration in CI users. For duty cycle, we tested 65, 75, and 85% cycles. For interruption rate, we tested 1.5- and 5-Hz rates. Our RM ANOVA analysis, which we admit was underpowered, revealed no effects of interruption type or interruption rate. We did find a significant main effect of duty cycle, which indicated that increasing the amounts of speech available to the listener within each speech segment resulted in better performance overall. However, duty cycle did not interact with interruption type, meaning this usefulness of greater amounts of speech information did not boost restoration. No interactions were found to be significant with this analysis.

The third goal was to measure whether intact baseline sentence understanding scores were correlated with restoration benefits; this was found for a 50% duty cycle condition in the original paper (untested here), but not for the 75% duty cycle condition in the original paper (tested here). Like the original study, we found no significant correlation between performance in the replicating condition and baseline speech understanding. In addition, we did not find significant correlations between performance in any of the tested conditions and baseline speech understanding, even those closer to the 50% duty cycle tested in the original paper (i.e., the 65% duty cycle condition with 1.5-Hz interruptions).

On the one hand, perhaps the resources used in difficult listening conditions like a 50% duty cycle are not marshalled for the easier 65% duty cycle condition. On the other hand, the closest our correlations' *p*-values came to our alpha level was for the 1.5-Hz interruption rate, 85% duty cycle condition, which would not be predicted to show any effect of baseline speech understanding scores per the original paper.

A final goal for this study grew out of concerns that perhaps the IEEE sentences simply were not "restorable" given the parameters tested. That is, perhaps CI users were not, on average, showing restoration effects because even a NH listener with clear bottom-up acoustic information and comparable top-down knowledge would fail to show restoration effects with these materials. IEEE sentences were shown to be restorable in Jaekel et al. (2018), but at different parameters than those used in the present experiment. To measure IEEE sentence restorability with our current parameters, we initially tested two NH adult listeners on unprocessed versions of the stimuli used in this experiment. Unfortunately, the two NH listeners performed at ceiling in almost every condition, meaning no restoration effect was observed (that is, there was no "room to grow" from the silent-gap interrupted conditions, since participants were performing so well already in such conditions). Therefore, we tested a different NH adult listener with 32-channel noise-vocoded versions of the sentences. This adult listener was comparable in age to the CI users in both the original and replication studies (age = 53.9 years). This listener did not perform at ceiling across conditions, and thus was able to show a restoration effect in every condition tested. We therefore concluded that the sentence material was restorable with our parameters even with some acoustic degradation to the bottom-up acoustic cues; however, clearly, the vocoder fails to capture the full CI listening experience, as many of our CI users failed to show restoration.

Our replication of the original CI restoration paper was not perfect; first, our sample was slightly older and had poorer baseline speech understanding scores compared to the sample in the original paper. Second, we tested some conditions that were not tested in the original paper, which may have affected how participants performed on the replicating condition, as the task was slightly different. Third, our participants were native English speakers completing the study in English, while the original study was performed with Dutch speakers in Dutch. This necessitated the use of a different sentence corpus than that used in the original study, which could have differed in other ways from the original corpus (e.g., our sentences could have been harder to comprehend in some manner). Fourth, there were several other small differences between our study and the original study that may have had an effect on performance, for example using two loudspeakers rather than one, having the experimenter control the experiment rather than it being self-paced by the participant, etc. Overall, however, we believe we have come close to repeating the target condition used in the original study, and thus our results can be compared to the original study's.

To summarize, the lack of restoration effects observed in Experiments 1-3 is less concerning given the results of Experiment 4, where we failed to replicate a previously reported finding by Bhargava et al. (2014) that CI users *should* be able to restore speech. We did find considerable variation in our participants in terms of restoration, just as was found in the original study, but this variation did not lead to an overall average effect of positive restoration benefits. Furthermore, the parameters used to measure restoration did not clearly elicit patterns in results: for example, one might expect higher duty cycles to result in more restoration (Bhargava et al., 2014), but this was not always the case; sometimes less frequent interruptions resulted in restoration, while other times more frequent interruptions resulted in restoration. In general, our results suggest that individuals with CIs do not show consistent perceptual restoration – both within and across participants. This has important implications for real world listening in noise, which will be addressed in the conclusions chapter.

Chapter 6: Conclusion

CI users are less successful at understanding speech in noisy listening environments compared to NH listeners (Fetterman & Domico, 2002). While noise reduction algorithms in CI front-end preprocessing generally appear to improve speech understanding in noise (Gifford & Revit, 2010; Mauger et al., 2014; Wolfe et al., 2015), one question is whether these algorithms, along with other CI-related variables, might be negatively affecting the use of a speech repair mechanism called perceptual restoration (Warren, 1970). Removing noise from a speech signal interruption reduces, rather than improves, understanding; the presence of noise in a speech signal interruption can cause the listener to perceive the interrupted word as intact and the noise as a separate, irrelevant auditory object. This illusion of intactness results in better speech understanding, as the interrupted speech has been "repaired," or perceptually restored, by the brain. CI users sometimes fail to show perceptual restoration in conditions where NH listeners can take advantage of the mechanism (Bhargava et al., 2014). This dissertation aimed to discover the extent to which device and listener factors reduced or improved perceptual restoration in CI users. Strengthening perceptual restoration in CI users could improve their ability to understand speech in noisy, realistic listening environments.

In order to achieve perceptual restoration, three main elements are needed: (1) the presence of a plausible masker (Bashford et al., 1992; Başkent, 2012); (2) access to high-quality bottom-up acoustic information, for example, so that maskers may be adequately distinguished from the target signal (Bashford et al., 1992; Başkent, 2012; Bhargava et al., 2014; Jaekel et al., 2018); and (3) opportunities to use top-down linguistic knowledge (Başkent et al., 2016; Bregman, 1990; Samuel, 1981; Shinn-Cunningham & Wang, 2008).

The presence of a plausible masker is potentially affected by noise reduction algorithms in CI front-end preprocessing (Experiment 1) and compression, which changes the effective SNR (Experiment 2). The quality of bottom-up acoustic information may vary in bilateral CI users who have a “poorer” and “better” ear – meaning their ears experience different levels of signal degradation, potentially due to factors like duration of hearing loss and electrode/nerve interface (Experiment 3). Providing semantic cues may increase opportunities for CI users to apply top-down knowledge to incoming signals, but this could be less possible in CI users who experienced hearing loss prior to spoken language development (Experiment 3). Thus, this dissertation aimed to evaluate CI users’ restoration abilities across all three main elements.

6.1 Device factors affecting perceptual restoration in CI users

We hypothesized that both noise reduction algorithms in CI front-end preprocessing and compression algorithms would reduce restoration in CI users, as they were expected to affect the plausibility of interrupting noise serving as a masker. Although such algorithms may boost speech understanding in noise in general, increasing opportunities to utilize restoration in noisy environments could result in improved outcomes.

Experiment 1 evaluated whether disabling CI front-end preprocessing features improved performance in the restoration paradigm. Despite choosing parameters that have elicited restoration in CI users in our own pilot testing and in previous work in the area (Bhargava et al., 2014), we found no restoration either with or without CI front-end preprocessing. Thus, we could not make any conclusions as to whether restoration was affected by noise-reduction algorithms. While we cannot speak to restoration benefits, we found that the availability of CI front-end preprocessing did particularly improve noise-burst interrupted speech understanding. Therefore, the noise-reduction algorithms served their purpose: making it easier for CI users to perceive noise-interrupted speech signals, potentially via reducing the signal distortions introduced by loud, sudden noise bursts.

Experiment 2 evaluated whether compression reduced perceptual restoration in CI users. The level of incoming signals is decreased by a compression algorithm above a certain intensity level; we wanted to determine if the levels of our interrupting noises were being reduced by compression, thus reducing their plausibility as maskers in the restoration task. We presented stimuli at levels that either would or would not engage compression, with the expectation that when compression was engaged, restoration would be reduced. As in Experiment 1, we found no restoration at either sound level, and thus were unable to determine whether compression affected restoration ability. Speech understanding with noise-burst interrupted speech was best in the most intense condition, when compression was expected to be engaged. Noise-interrupted speech was possibly easier to process in the more intense condition because the effective SNR was changed to be more favorable; however, again, we found no evidence that CI users were able to utilize noise bursts to perform speech repair.

To summarize, we were unable to conclude whether device factors negatively affected restoration, as we were unable to detect restoration in CI users in general. CI users do not appear to perceive noise interruptions as prompters of restoration, but as interferers to speech processing. Previous work has found that CI users may qualitatively perceive noise differently from NH listeners (Oxenham & Kreft, 2014), so perhaps their approach to processing speech in the restoration paradigm is also qualitatively different from that of NH listeners. For example, current spread is known to reduce CI users' utilization of temporal envelope modulations during speech processing (Oxenham & Kreft, 2014); it is possible that the temporal changes introduced by silent-gap interruptions were less detectable to CI users, and thus had less of an impact on speech understanding. In comparison, noise-burst interruptions could have introduced forward and backward masking that affected speech signals surrounding the burst and/or introduced auditory distraction, thus reducing speech understanding. Overall, noise-reduction algorithms and compression appeared to work as intended – improving speech-in-noise understanding in general – but whether they allow opportunities to use speech repair, which could further improve communication outcomes in noisy environments, remains an open question.

6.2 Listener factors affecting perceptual restoration in CI users

Experiment 3 evaluated how the factors of bottom-up acoustic signal quality and opportunities to use top-down knowledge affected restoration in CI users. To test the former, we presented interrupted sentences to either the "better" (assumed higher signal quality) or "poorer" (assumed lower signal quality) ears. To test the latter, we provided a semantic cue prior to half of the sentences, which was meant to prime listeners to the content of the upcoming sentence. While some CI users showed restoration benefits in certain conditions of Experiment 3, no pattern emerged and our statistical model failed to detect average restoration benefits. Instead, we found that top-down knowledge was able to interact with any quality of bottom-up acoustic signal to produce an increase in speech understanding, and that having presumably higher-quality bottom-up acoustic information did not boost noise-burst interrupted speech understanding, contrary to previous restoration work with degraded signals (Başkent, 2012; Clarke et al., 2016; Jaekel et al., 2018).

When CI users were grouped based on hearing histories and other participant variables, we found that older CI users with asymmetrical ears could achieve restoration benefits, while CI users with symmetrical ears did not. The asymmetry in hearing histories across ears itself may not be relevant; rather, the ability to repair speech may be due to the fact that these listeners had the longest exposure to normal hearing in one ear out of all participants in the study. While this group showed particular benefits with processing interrupted speech in general when they could utilize top-down knowledge and received high-quality bottom-up acoustic signals, their restoration ability was not dependent on these factors. Therefore, in CI users, it may be the case that extensive experience repairing speech signals with a NH ear may be necessary to achieve restoration with the device. Note that this finding was based on data from only a few participants, meaning the majority of the CI users we tested did not show any restoration. This again points to a possible qualitative difference in how CI users, in general, approach the processing of noise-burst interrupted signals compared to NH listeners.

6.2.1 Restoration in prelingual vs. postlingual adult cochlear implant users

Some participants in our studies experienced non-normal hearing prior to language development, meaning they had "prelingual" hearing loss and/or deafness. This may have impacted how these CI users were able to use restoration, a skill requiring the use of top-down linguistic knowledge. With the implementation of universal newborn hearing screenings, hearing loss is now often detected much earlier in life than in the past, and with the invention of CIs and FDA allowances for early implantation, children with severe hearing losses are receiving auditory input at much younger ages. However, we tested mainly older adults who were less able to take advantage of early detection and early implantation; our prelingual adults had long durations of non-normal hearing and had to, as children, develop language without clear auditory input (Pisoni, 2000). This development would include learning how to restore interrupted speech signals, as perceptual restoration is a skill that is believed to be developed over time rather than innate. Specifically, the restoration skill appears to be absent in NH toddlers (Newman, 2006) and developed (or in the midst of being developed) by 4-6 years in NH children (Ackroff, 1981; Koroleva, Kashina, Sakhnovskaya, & Shurgaya, 1991; Newman, 2004; Walley, 1988; Winstone, Davis, & de Bruyn, 2012).

One hypothesis is that prelingual CI users would not show any restoration: having less robust lexical representations containing less acoustic-phonetic detail (due to never having access to clear speech) could make it more difficult to match incoming interrupted speech to stored representations during speech repair (Rönnberg, Rudner, Foo, & Lunner, 2008). This could lead to prelingual CI users relying more on bottom-up acoustic information instead of utilizing top-down linguistic knowledge to restore speech. In fact, our prelingual CI users did restore speech in certain cases – for example, in Experiment 4, several prelingual CI users showed restoration benefits. Therefore, it appears that prelingual CI users can develop restoration skills even without rich auditory input. Like their postlingual peers, however, they fail to consistently use this skill to repair noise-interrupted speech (Experiments 1-3). While it is difficult to make strong conclusions based on such variable results, perceptual restoration development may be due to maturation rather than exposure to and experience with auditory signals. As discussed below, future work could focus on the effects of auditory signal quality and quantity on perceptual restoration development in children with CIs.

6.3 Replicating previous work in restoration

Prior to the present study, Bhargava et al. (2014) was the only published study to have directly tested restoration in CI users. We wanted to determine if we could replicate the restoration effects observed in some of the conditions in that original study, since we struggled to find consistent restoration effects in any of our experiments. Despite closely matching the methods used by Bhargava et al. (2014), we could not reproduce the positive restoration benefits they observed using their specific interruption parameters. Instead, we found restoration benefits in a condition with less frequent interruptions, but more speech information missing, and in a condition with more frequent interruptions and less speech information missing. Partly due to the large variability in performance in our sample, and partly due to the small size of these restoration benefits, no combination of parameters yielded statistically significant restoration benefits. Thus, once again, no consistent restoration was observed among the CI users tested – matching the null findings found in our other experiments. Not only could we not elicit restoration in CI users by varying device factors and listener factors (Experiments 1-3), we could not elicit restoration by varying factors pertaining to the signal itself (Experiment 4).

6.4 Limitations

The present study was affected by some limitations. Despite pilot testing and prior work in the area (Bhargava et al., 2014), we were unable to set interruption parameters that allowed us to find a baseline restoration ability in our CI users. Because we could not elicit this baseline, we were unable to detect the impacts of noise-reduction algorithms and compression on restoration. Future work should consider administering a pre-test for each participant to determine the best interruption parameters to elicit restoration for that individual, if perceptual restoration in CI users is possible.

As front-end preprocessing algorithms in CIs are proprietary, there is little available information as to how the algorithms specifically work. While we expected to see effects of SNR-NR and other algorithms in the restoration paradigm, it was decidedly unclear how exactly the algorithms were changing the incoming speech signals. Knowing how the interrupted speech signals are affected by the noise-reduction algorithms and compression could allow us to create stimuli that can be more effectively manipulated to measure potential restoration effects. For example, if we knew the exact attack time for the SNR-NR algorithm, we could interrupt our stimuli with noise bursts that have durations that consistently elicit attack time effects.

We had hoped that our sample of CI users would have clear “poorer ear” and “better ear” distinctions. In fact, our sample had quite symmetrical hearing histories, and often had little difference in speech understanding performance between their ears. To better determine the impact of bottom-up acoustic quality, a sample with more diverse, asymmetrical hearing histories should be recruited. Such a sample could include CI users with single-sided deafness or partial array insertions. CI users with single-sided deafness have one ear with acoustic hearing and one ear with electric hearing; thus, the effects of bottom-up acoustic information quality on restoration, if any exist, would most likely be detected in this group of listeners.

6.5 Future Directions

Studying the effects of listening effort and fatigue on perceptual restoration in CI users could elucidate the extent to which these factors might have affected performance, and contributed to the lack of restoration benefits, in the current project. Anecdotally, some CI users in the present study commented that the noise bursts were distracting and/or irritating. Others commented that the provision of semantic cues in Experiment 3 was sometimes frustrating (e.g., when they were unable to process the sentence, and felt like they should be able to because they had access to a “hint”) and/or confusing (e.g., when they felt they had to process too many things at once – holding a visually presented word in their memory while trying to listen to an interrupted sentence). The lack of restoration benefit could be because processing noisy sentences drains cognitive resources and requires greater effort than processing sentences with gaps (Finke, Sandmann, Kopp, Lenarz, & Büchner, 2015). The lack of benefit could also be due to a conscious choice on the part of the participants to refuse to evaluate difficult, noisy sentences in the first place, potentially due to fatigue. There exist several procedures for measuring listening effort in CI users, including pupillometry (Perreau, Wu, Tatge, Irwin, & Corts, 2017; Winn & Moore, 2018), dual-task paradigms (Hughes & Galvin, 2013), self-report, and ERP measures (Finke et al., 2016). Understanding the interaction of restoration and listening effort might be helpful; it could be that in highly effortful listening situations, people demonstrate reduced restoration ability.

Perceptual restoration in CI users has only been studied in adults thus far; measuring perceptual restoration in children with CIs could reveal the extent to which the developmental time course of the mechanism is affected by exposure to degraded auditory input. By comparing the development of restoration in children with CIs to NH children, this line of work could determine whether children with CIs are delayed in learning to utilize top-down knowledge during spoken language processing in difficult listening environments. Poor signal quality could slow the speed with which children learn to integrate top-down and bottom-up information; alternatively, consistently degraded bottom-up acoustic information could encourage children to begin to rely more heavily on top-down knowledge at earlier ages. Furthermore, the FDA has approved that pediatric CI users over the age of six can have activated front-end preprocessing, meaning that the effects of noise-reduction algorithms on the development of restoration skills could also be evaluated.

6.6 Final Conclusion

CI users fail to consistently repair noisy speech signals. Device factors like front-end preprocessing and compression, which were believed to impact the plausibility of noise as a masker (and thus the plausibility of the restoration illusion), neither inhibited nor promoted restoration. Similarly, listener factors like bottom-up signal quality and top-down linguistic knowledge use, whose integration is believed to be key to repairing speech, did not produce a restoration effect. While the perceptual restoration framework appears to function for NH listeners, the processing of noise-burst interrupted speech may be qualitatively different in CI users, and thus may require different parameters in order to function correctly. Noise generally serves more as an interferer rather than a promoter of speech repair in this population. Perceptual restoration, then, may not be a useful tool for CI users attempting to understand speech in noisy environments, and the inability to utilize restoration may be a contributor to this population's general difficulties understanding speech in noise.

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