Lexical Access in the Face of Degraded Speech: Adapting to Moment by Moment Uncertainty

Running Head: LEXICAL ACCESS AND DEGRADED SPEECH

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Author Note

This research was supported by NIH Grants DC008089 awarded to Bob McMurray, and DC000242 to awarded to Bob McMurray and Bruce Gantz.

We have no conflicts of interest to disclose.

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Abstract

Listeners often process speech in adverse conditions. One challenge is spectral degradation, where information is missing from the signal. Lexical competition dynamics change when processing degraded speech, but it is unclear why and how these changes occur. We ask if these changes are driven solely by the quality of the input from the auditory periphery, or if these changes are modulated by cognitive mechanisms. Across two experiments, we used the visual world paradigm to investigate changes in lexical processing. Listeners heard different levels of noise-vocoded speech (4- or 15-channel vocoding) and matched the auditory input to pictures of a target word and its phonological competitors. In Experiment 1 levels of vocoding were either blocked together consistently or randomly interleaved from trial-to-trial. Listeners in the blocked condition showed more differentiation between the two levels of vocoding; this suggests that some level of learning is in effect to adapt to the varying levels of uncertainty in the input. Exploratory analyses suggested that when less intelligible speech is processed there is a cost to switching processing modes. In Experiment 2 levels of vocoding were always randomly interleaved. A visual cue was added to inform listeners of the level of difficulty of the upcoming speech. This was enough to attenuate the effects of interleaving as well as the switch cost. These experiments support a role for central processing in dealing with degraded speech. Listeners may be actively forming expectations about the level of degradation they will encounter and altering the dynamics of lexical access.

In the real world, listeners frequently process speech in many types of adverse conditions. A talker may not produce speech tokens that match the listeners' expectations due to talker differences or accented speech. Environmental conditions may lead to lower quality input (e.g., background noise, electronic transmission limits). In some cases, the listener herself may contribute to difficulties (e.g., hearing loss). These challenges impact distinct aspects of speech processing (for review, see Mattys et al., 2012).

There are two routes by which individuals might adapt to adverse listening conditions. First, in some cases speech cues are systematically altered, and listeners can remap the new perceptual input to their stored lexical templates. This is plausible, for example, when coping with novel accents. Perceptual learning occurs as listeners are repeatedly exposed to these lawful differences and recognition improves.

Second, sometimes information is simply missing. This is the case with hearing loss, background noise, or limits in electronic communication. When information is missing, remapping may not be sufficient. Instead, listeners may need to modulate higher-level processing (e.g., lexical access) to cope. They must prepare to make more frequent perceptual mistakes by minimizing the likelihood of a mistake or minimize the cost of one.

Noise vocoded speech, used here, illustrates both processes. Noise vocoding divides the speech signal into separate frequency bands and uses the amplitude envelope in each frequency band to filter white noise. This process results in speech that preserves the envelope of the original signal but degrades much of the spectral information (much like a Cochlear Implant [CI]). The intelligibility of this speech varies depending on the number of frequency bands. Vocoded speech with ten or more bands can generally be readily understood without training, though speech with four frequency bands can often only be intelligible with sufficient exposure

or training (Davis & Johnsruide, 2003; Shannon, Zeng, Kamath, Wygonski, & Ekelid, 1995). Listeners can rely somewhat on perceptual learning to emphasize envelope over spectral cues and remap the vocoded input to stored lexical templates. However, there is also fundamentally less information available in noise vocoded speech. Thus, listeners may also prepare for uncertainty.

Perceptual learning has received substantial attention (Bradlow & Bent, 2008; Francis, Nusbaum, & Fenn, 2007; Johnsruide, Carlyon, Taylor, Hervais-Adelman, & Davis, 2010; Lively, Logan, & Pisoni, 1993; Norris, McQueen, & Cutler, 2003), but the latter process of preparing for uncertainty has received much less. The goal of this paper is to examine the latter, in the context of noise-vocoded speech, which provides an analogy to CI users who face this problem on a daily basis. We begin with a short review of perceptual learning as this is crucial for understanding when and how listeners prepare for uncertainty.

Perceptual Learning

In many adverse listening situations, the cues in the signal are not what the listener is accustomed to processing but are still lawfully related to the idealized speech signal. For example, when a listener encounters an unfamiliar accent, the speech input differs in lawful and predictable ways from their expectations. Listeners can potentially cope with this adversity by retuning perceptual processing, and a wealth of evidence suggests a highly plastic system.

The lexical system rapidly retunes speech categorization based on experience with ambiguous input (Norris et al., 2003). For example, when encountering a speaker who systematically produces a phoneme (like /s/) ambiguously (halfway between /s/ and /ʃ/) they shift their boundary (Clopper & Pisoni, 2004; Lively et al., 1993; Myers & Mesite, 2014). Listeners

can also adapt rapidly to foreign accents from both familiar and novel speakers after proper exposure (Bradlow & Bent, 2008). CI users must also retune their speech categorization processes as CIs reduce the spectral cues available in the input while preserving the envelope cues. Appropriately adapting to the cues available in the auditory input over time allows CI users to reach good speech recognition outcomes (Cullen et al., 2004).

Lexical and semantic processing may help to drive these rapid adaptations. Much of this work has used noise vocoded speech. Davis et al. (2005) showed that brief exposure to noise vocoded sentences leads to improvement in recognition accuracy. While all listeners improved as the experiment progressed, those that heard the sentence repeated in clear speech after the vocoded speech showed more gains than to those who heard the vocoded sentence prior to the clear speech. This suggests that adaptation is more rapid when the target speech is known prior to hearing the vocoded speech. Similarly, listeners who were trained on vocoded sentences showed greater performance than to listeners trained non-words. Thus, higher-level language information plays a critical role in listeners adapting to process vocoded speech input (see also Hervais-Adelman et al., 2008). Furthermore, Johnsrude et al. (2010) showed that brief exposure to noise vocoded sentences in specific frequency-regions led to gains that transferred to another frequency region. However, when the carrier signal varied between exposure and test (noise band, pulse trains, and sine waves), generalization and transfer of learning was much lower.

Taken together, these results suggest that listeners can rapidly adapt to sub-optimal speech input so long as the cues are somewhat consistent in how they differ from ideal speech. This adaptation occurs quickly and is driven by top-down influences. One way this may be accomplished is by simply changing cue weightings during phoneme categorization and rely on secondary cues when primary cues are unavailable (Kim, Clayards, & Kong, 2020).

While adaptation can improve word recognition, it often does not lead to performance that is equivalent to listening in ideal conditions (Shannon et al., 1995); that is asymptotic performance with vocoded speech is far from what they can achieve from non-vocoded speech in quiet. This suggests a need to reconfigure the system to cope with uncertainty.

Adapting to Uncertainty

These findings suggest that some of the difficulty with things like noise vocoded speech is that information is missing from the signal. Listeners may cope with this in a number of ways. First, listeners may alter higher-level processing to cope with missing information. For example, they could alter sentence processing or down weight the auditory input as a whole and rely instead on non-auditory cues or the discourse context. Second, the speech system may adapt to minimize either the likelihood of a misperception, or the cost of a misperception when it occurs. When misperceptions occur from missing information, they are likely to occur at the phoneme level or below. Listeners may incorrectly categorize a /b/ as a /p/ or simply miss a phoneme. When the listening scenario is likely to lead to such misperceptions, how might listeners minimize their negative impacts? Lexical processing could be important for this in two ways.

First, the lexical level is critical for mapping sound onto meaning, the phoneme level is not (as long as the listener accesses the correct word). Thus, mechanisms that ensure that word recognition is accurate (even in the face of a phoneme error) may help. Critically, words span multiple phonemes and thus lexical processing can rely on additional phonemes to access the correct word when a phoneme level misperception occurs. As a result, when the input is particularly challenging, listeners could slow down lexical processing to minimize the likelihood of that a misperception of a single phoneme can derail the process. Delaying would allow

listeners to use more complete information about a word to activate the appropriate lexical candidate rather than committing early and then needing to recover from a misperception. This might allow for listeners to correctly recognize a word even if they misperceive an individual phoneme, minimizing the likelihood of a lexical-level error.

Second, lexical processing could be tuned to minimize the cost of an error. In many cases, a word-level error may be corrected by later sentential or discourse context (Brown-Schmidt & Toscano, 2017; Kapnoula et al., in press.; McMurray et al., 2009). However, recovering from such “garden paths” could be difficult. Consequently, listeners might tune lexical processing to keep competitors active longer; this in turn could help them recover when word-level misperceptions occur.

Thus, the lexical system is an ideal locus for processing changes that could help listeners cope with missing information, by minimizing both the likelihood and the consequences of an error. Current theories of word recognition in quiet offer several ways this can be accomplished.

Lexical Competition and Access

The primary challenge confronted by models of lexical access is the temporary ambiguity inherent to spoken language. Speech unfolds over time, and this leads to brief ambiguity about the intended target word, even in ideal listening circumstances. For example, while hearing *wizard*, at onset the input *wi-* is consistent with many possible words (*wizard*, *whistle*, *window*...). To cope with this, listeners map sound onto meaning immediately as they receive any amount of input (Allopenna, Magnuson, & Tanenhaus, 1998; Zwitserlood, 1989), activating many lexical candidates that are consistent with the input thus far (Dahan & Gareth Gaskell, 2007; Marslen-Wilson, 1987). This mapping process is flexible and may partially consider words

that do not share onsets with the target but overlap in other ways (such as rhymes: Allopenna et al., 1998; or anadromes: Toscano et al., 2013). Lexical candidates compete in parallel during processing and the more active candidates actively inhibit their competitors (Dahan, Magnuson, & Tanenhaus, 2001). This process is resolved when one lexical candidate receives sufficient activation and suppresses alternatives.

Classic effects suggest this competition process is inherently well suited to cope with ambiguity. For example, frequency effects allow some words to have stronger activation with less direct support from the input (Dahan et al., 2001; Marslen-Wilson, 1987). This could potentially help when information is missing as a form of prior expectation. Additionally, the fact that rhymes (e.g., *lizard* when the target was *wizard*) and anadromes are active even after disconfirming information has occurred in the signal (differing onsets) suggests that the lexical system can maintain a lot of potential options (Allopenna et al., 1998; Connine, Blasko, & Titone, 1993; Dufour & Grainger, 2019; Gregg, Inhoff, & Connine, 2019; Marslen-Wilson, Moss, & Van Halen, 1996; Toscano et al., 2013). These types of competitors could help listeners revise hypotheses about the input flexibly when lexical access fails in a variety of ways. Thus, the way in which lexical candidates can become active and compete with one another is far more flexible than a simple recoding of the perceptual input as it is received. Crucially, even without modification, these mechanisms may be helpful for uncertain listening conditions.

However, there may be further modifications that are beneficial. Most models of spoken-word recognition propose two roughly distinct aspects of lexical 1) early activation of lexical candidates that are consistent with the unfolding input, and 2) later suppression of non-matching competitors. Changes in both of these processes could be particularly useful for dealing with uncertainty. For example, the Cohort model (Marslen-Wilson, 1987; Marslen-Wilson & Welsh,

1978) allows for multiple lexical candidates which were initially supported by the input to become active but also uses contextual information to help restrict some candidates. Shortlist (Norris, 1994) similarly makes distinctions about initial lexical access, when lexical hypotheses are generated based on the input, and lexical competition, when incorrect hypotheses are ruled out. The TRACE model of speech perception (McClelland & Elman, 1986) proposes similar activation through bottom-up input, but claims that at both the phoneme and lexical level within-level competition and decay occurs, and these may take longer to engage. While these models differ in mechanistically important ways, all functionally differentiate initial activation from resolution of competition.

Such a system could in principle be altered when listening conditions are challenging. For example, listeners could slow lexical processing to decrease the impact of misperceiving any single phoneme on recognition (McMurray, Ellis, & Apfelbaum, 2019). Additionally, listeners could sustain activation for competitors based on the quality of the input. This could allow listeners to more easily recover from mispronunciations in situations where they are more likely to occur (Farris-Trimble, McMurray, Cigrand, & Tomblin, 2014). These alterations would be particularly evident in the dynamic time course of lexical access.

Several studies examine the dynamics of lexical competition for words in background noise (Ben-David et al., 2011; Brouwer & Bradlow, 2016). They find that competitor activation increases as listeners tolerate greater signal-to-target mismatch in the input, or that it may be preserved over the course of processing (e.g., not suppressed as rapidly). In the case of broadband noise, overall competition increases as both cohort and rhyme items are more active. This sustained competitor activation would allow for easier recovery from misperceptions.

It is unclear whether these changes are an automatic consequence of the poor reliability

of the signal (e.g., the words are just more confusable), or if they represent a true cognitive adaptation. However, there is evidence that the expectation of an unreliable signal can impact patterns of lexical access, even when the word itself is unmodified. McQueen and Huettig (2012) used carrier sentences in which single phonemes were masked with noise throughout the carrier. Critically, the target word was always clearly produced. When the carrier sentences contained these bursts of noise, the cohort was less active while the rhyme was more active. This suggests that such changes are in part cognitive.

Several studies have also examined spectral degradation either in CI users, or with NH listeners hearing vocoded speech. In these listeners lexical access is generally delayed and, in the most adverse conditions, lexical competition qualitatively differs from ideal listening conditions (Farris-Trimble et al., 2014; McMurray, Farris-Trimble, & Rigler, 2017). This has shown two clear patterns. First, for good performing post-lingually deaf CI users and normal hearing (NH) listeners experiencing moderately difficult noise vocoded speech (8-channel), a small delay in lexical access is observed and competitor activation may be sustained. This sustained activation pattern may be the result of listeners committing less fully to the target word in order to better recover from misperceptions in scenarios in which they are likely to occur (McMurray et al., 2019).

In contrast, for pre-lingually deafened CI users and NH listeners listening to highly degraded speech (e.g., 4-channel noise vocoding) the delays are substantially larger (>200 msec). This leads to a different pattern of lexical competition. Because of this delay, cohorts are less active than expected, since by the time lexical access initiates more of the word has been heard and the cohort can be ruled out. At the same time offset competitors are more active. In effect, it appears that listeners in these circumstances show a “wait-and-see” approach to lexical access

rather than the normal incremental processing observed. It is not yet clear the degree to which this reflect an automatic consequence of poor input or if it is an adaptation of some kind.

The Present Study

The mechanisms of lexical access clearly change depending on the quality of the input. It is unclear why these changes in the dynamics of lexical access occur, and if they exhibit the kind of flexibility that listeners would need to cope with different challenging listening conditions.

There are at least two possibilities. First, these differences in lexical access may simply be automatic consequence of receiving under-informative auditory input; that is the enhanced lexical competition simply reflect the fact that words are more perceptually confusable. This is unlikely given the results of McQueen and Huettig (2012), but this study used a rather unorthodox version of the visual world paradigm in which the target object was not on the screen on critical trials. Thus, it is worth a second look at this question. Second, these differences may be the result of additional cognitive adaptations which modify parameters of the lexical system in potentially multiple ways to deal with uncertainty. What is unclear is the degree of *flexibility* that listeners possess. We study that here along two dimensions.

First, Huettig and McQueen (2012) provided a single level of disruption (periodic bursts of noise). In the present study, we ask if listeners can adapt to *multiple* levels of signal degradation within a single session. If listeners can adopt separate processing strategies for distinct levels of signal quality, are these changes in processing based solely on the quality of the input from trial to trial, or are they based on longer-term adaptations? The timescale of these changes may offer critical evidence. If these adjustments simply reflect the poor input, they should be very rapid—responding to the level of clarity in the moment. However, cognitive

adaptations may require repeated exposure to input of a consistent quality.

To disentangle these hypotheses, Experiment 1 presented listeners with either blocked or interleaved levels of noise vocoding in a visual world paradigm experiment. In the blocked condition, listeners heard one of the two levels of noise vocoding in four blocks of 120 trials. In the interleaved condition, listeners were randomly presented one of two levels of noise vocoding on each trial. In the blocked condition all 120 trials came from the same condition, giving a strong context cue as to the reliability of the signal. If the previously observed changes in lexical access (due to vocoding) are the result of cognitive adaptations, we would expect that interleaving should eliminate or reduce the differences between the two levels of vocoding because it would prevent this adaptation. If instead, the changes in lexical access are the result of the poor quality of the input alone we would expect the blocked and interleaved conditions to have similar results for the two levels of vocoding.

Second, if listeners show evidence for cognitive adaptations, we ask how quickly they can adjust, and on what sources of information (e.g., abstract expectations, vs. learned experience of the stimuli), and if there is effort involved. This was examined in Experiment 2 by manipulating listener's expectations in an interleaved design.

Both experiments used 4-channel- and 15-channel-vocoded speech. The 4-channel vocoding was intended to encourage a “wait-and-see” approach (as in McMurray et al., 2017) while the 15-channel vocoding was easily intelligible and intended to encourage early incremental processing much like speech in quiet listening scenarios.

Experiment 1

Methods

Participants. Sixty monolingual English speakers participated in this experiment. All participants reported normal or corrected-to-normal vision and normal hearing. Participants were students at the University of Iowa and received course credit as compensation for participating in this experiment. Participants provided informed consent in accordance with Institutional Review Board approved protocols. Five were excluded from analysis due to technical issues with data collection and three participants were excluded due to low overall looking throughout the experiment. This left 26 participants in each of the two experimental groups.

Design. This experiment used 30 item-sets each containing four words (half one-syllable words, half two-syllable words). Every item-set consisted of a base word (target, e.g., *butter*), a cohort (e.g., *button*), a rhyme (e.g., *putter*), and an unrelated item (e.g., *whistle*). This resulted in a total of 120 words. Pictures of each of the words always occurred together during a trial. Each word within a given item set was used as the target on different trials during the experiment. Each word was heard a total of four times across the experiment (with a different token of the word used each time) for a total of 480 trials.

This led to four trial types. When the base word (*butter*) was the target word, this created a target, cohort, rhyme, unrelated trial (TCRU). When *button* served as the target, this led to a target, cohort, unrelated, unrelated (TCUU) trial as both *putter* and *whistle* were unrelated to *button*. Similarly, when *putter* was the target, this led to a target, rhyme, unrelated, unrelated (TRUU) trial as *button* and *whistle* were unrelated. When *whistle* was the target, this led to a trial where all the other pictures were unrelated (TUUU).

Two primary factors were manipulated. The first was the number of channels in the noise-vocoded stimuli (the difficulty), which was manipulated within-subjects (half of the trials were 4-channel, the other half were 15-channel). The second factor was the manner in which the

two levels of difficulty were presented (between-subject). Participants in the blocked condition heard a consistent level of vocoding for 120 trials, before switching to the alternate level (the initial level of noise vocoding was counterbalanced across participants). This led to four blocks of trials which alternated between the two levels of vocoding. The interleaved participants heard the two levels of noise vocoding randomly interleaved such that there was no way to predict what the level of spectral degradation would be on any given trial.

Stimuli. Auditory stimuli were recorded by a female speaker with a Midwestern dialect. Words were recorded on a head mounted microphone in a sound attenuated room and digitized at 44,100 Hz by a Kay 4300B A/D board. Each word was recorded in the carrier phrase “he said X” and then excised from the phrase. Eight recordings of each phrase were made and the clearest four were selected for use in the experiment. One hundred milliseconds of silence were added to the beginning and the end of each word and then all stimuli were amplitude normalized.

Visual stimuli were clip art images created using a lab procedure designed to ensure that each image is easily recognizable as the intended word (McMurray, Samelson, Lee, & Tomblin, 2010). For each image, multiple candidates were selected from a commercial clipart database. A focus group of lab members reviewed the images and chose the most canonical image and determined any edits needed. The image was then edited to ensure prototypical color, orientation, and size. The final image was approved by a senior lab member with experience with the visual world paradigm.

Procedure. The visual world paradigm task was implemented using Experiment Builder (SR Research Ltd., Ontario, Canada). All testing was carried out in a sound-attenuated booth to control for background noise. Participants were seated in front of a 17” LCD monitor operating at a resolution of 1280×1024 pixels. Auditory stimuli were presented over high-quality

headphones with a Samson C-Que 8 amplifier. Listeners were permitted to adjust the volume of presentation to a comfortable level.

Prior to the experimental task, each participant underwent a brief training phase during which they were exposed to each of the word / image pairs that were in the experiment. The participant was shown each image and its written label directly below it. This was self-paced. After this brief training, participants saw instructions for the visual world paradigm task.

On each trial, four images (300×300 pixels each) were displayed on the screen, one at each corner. Each image was 50 pixels away from the screen edge. Participants were shown a red fixation circle at the center of the screen to draw their attention. After 500 ms the circle turned blue and participants were instructed to click on the circle after this color change to begin the trial. After clicking the circle and auditory stimulus was played and participants were instructed to click on the picture that corresponded to the word they had heard. Participants were warned during the instructions that the speech they would hear would sound somewhat distorted and were told to make their best guess if they were unsure of what they had heard.

Eye-tracking recording and processing. An Eyelink II head-mounted eye tracker was used to record eye movements at 250 Hz during each trial. This tracks participants' point of gaze while controlling for head movements during the task. Both corneal reflection and pupil were used whenever possible. The eye tracker was calibrated using a standard nine-point Eyelink procedure. A drift-correct was performed every 20 trials to correct for drifts in the eye track over the course of the experiment. In the event of a failed drift correction the eye tracker was recalibrated before resuming the experiment.

The continuous recording was automatically classified into blinks, saccades, and fixations. Each saccade was combined with the following fixation point to form a single "look"

as has been done in previous studies (McMurray et al., 2010). Each look lasted from the initiation of the preceding saccade to the end of the fixation. Because trials ended at the response, not all trials had fixations late in the time course. To address this, we adopted the “object padding” approach of many prior studies (Allopenna et al., 1998; McMurray, Clayards, Tanenhaus, & Aslin, 2008). We set a fixed trial duration of 2,000 ms. For trials that ended before this point, we extended the last eye-movement; trials which were longer than 2,000 ms were truncated. This is based on the assumption that the participants’ last fixations reflect the word they “settled on”, and therefore should be interpreted as an approximation of the final state of the system and not necessarily what the participant was fixating at that time.

When identifying the object for each look, the boundaries for each image were extended by 100 pixels in each direction to allow for a small amount of error in the eye track. These extensions did not create overlap among the images on the screen.

When analyzing eye tracking data, only correct trials and looks occurring more than 200 ms after the onset of the auditory stimulus were included. Including only correct trials ensures that we assess real-time lexical activation when the end state of processing arrives at a correct perception. To analyze target fixations over time, we collapsed looks to the target across all trial types (TCRU, TCUU, TRUU, and TUUU). To analyze competitor fixations over time we collapsed across the two trial types during which the relevant competitor was present on the screen (TCRU and TCUU for cohorts; TCRU and TRUU for rhymes).

Results

We conducted two primary sets of analyses. The first examined the accuracy of the mouse-click as a function of level of degradation (4-channel or 15-channel noise vocoding) and

presentation condition (blocked or interleaved). The second examined the time course of fixations to targets and competitors across level of degradation and presentation conditions.

Accuracy. Accuracy was calculated for each subject and for each level of degradation. A 2×2 mixed ANOVA evaluate the effect of degradation (within-subject) and blocking (between-subject) on accuracy (logit transformed). There was a main effect of degradation level, $F(1,53) = 599.58$, $p < .001$. Not surprisingly, listeners showed much higher accuracy with 15-channel vocoded speech (97.95% accuracy) than 4-channel (86.34% accuracy). There was no significant effect of blocking condition and no interaction, both $p > .25$. The fact that blocking did not impact response accuracy suggests that interleaving levels of degradation does not impair the ability recognize this degraded input at the highest level. However, the effects of blocking may be easier to detect in online measures of lexical access.

Figure 1. Proportion of fixations to the four competitors on the screen as a function of time by level of degradation and presentation condition.

Time course of fixations: Descriptives and Approach. Figure 1 shows the probability of fixating a target or competitor over time. Listeners generally showed incremental processing in both the blocked and interleaved conditions with patterns of fixations that are typical of a TCRU design in the VWP. By about 400 ms, participants' eye movements were driven by the input, with listeners showing more target and cohort fixations (which match the early auditory

Figure 2. Fixations as a function of time by level of degradation (4-channel or 15-channel) and blocking condition (blocked or interleaved) for A) targets, B) cohorts, and C) rhymes.

input) than rhyme and unrelated (which do not). Shortly after 500 ms the target began to separate from the cohort as the participants heard later portions of the stimulus that rule out the cohort. Later in processing, rhymes show slightly increased fixations over the unrelated item. We see much slower dynamics of processing in 4-channel (left column) than 15-channel (right column), but few large differences between blocked (top row) and interleaved (bottom).

Figure 2 shows fixations to each class of competitors by level of degradation and presentation condition. Across all three competitor types, the patterns of fixations appear quite similar between the blocked and interleaved conditions. Figure 2A shows looks to the target. In both presentation conditions, participants showed a large delay in target fixations with more highly degraded speech input (a hallmark of a “wait-and-see” pattern). The reduced upper asymptote of looks to the target in 4-channel vocoding also likely reflects a less strong commitment to the lexical candidate even while selecting that item as the correct answer. Figure 2B shows looks to the cohort and exhibits another hallmark of the “wait-and-see” pattern: reduced peak fixations to the cohort for 4-channel vocoding. Finally, Figure 2C shows fixations to the rhyme and demonstrates the final component previously observed in the “wait-and-see” profile as rhymes are more active in 4-channel vocoding than in 15-channel. For both cohorts and rhymes, activation persists late into the trial (even after responses have been made) suggesting that participants may have been preparing for misperceptions to occur.

These data were analyzed using the Bootstrapped Differences of Timeseries (BDOTS) package in R Version 3.6.1 (R Core Team, 2015). BDOTS is used to detect differences in two different time series when the time window is unknown in advance. It reports precisely when differences are seen across the timecourse (Seedorff, Oleson, & McMurray, 2018).

In the BDOTS procedure, separate curves are fit to the time series data for each level of

degradation (4-channel and 15-channel), for each different word type (target, cohort, rhyme), for each participant. This fitting procedure smooths the data and allows for a parametric bootstrap to estimate the variance. These fitted curves are evaluated for goodness of fit based on their R^2 , and by a visual evaluation. The estimate the standard error of the curve for each condition at each time point is then estimated via bootstrapping. These standard errors were used to conduct two sample t -tests at each time point. This large number of t -tests raises the issue of family-wise error. However, these are not truly independent (as assumed in most family wise error corrections) as temporally adjacent tests are highly correlated. Thus, BDOTs computes a corrected alpha which takes advantage of the autocorrelation of the test-statistics to avoid being too conservative. When significant differences are found between conditions, we report the time window at which differences occurred, the direction of difference in proportion of fixations across the time window, the autocorrelation of the t statistic, and the adjusted alpha.

Each analysis used this approach to first compare 4-channel to 15-channel vocoding within a given blocking condition (blocked or interleaved). We then compared the difference between 4-channel and 15-channel vocoding across the two presentation conditions to determine if the size of the difference as a function of degradation is affected by the presentation condition.

Target fixations. Target fixations were fit by a logistic which models an initial period of low looking followed by a rapid increase to an asymptote. The variant used here had four parameters: the upper and lower asymptotes, the crossover (the time at which target fixations were halfway between the asymptotes), and the slope (the derivative at the crossover). A total of 104 curves were fit (two per participant, one for 4-channel vocoding and one for 15-channel vocoding). Of these, 103 had good fits ($R^2 > .95$) while one fit was slightly lower ($R^2 = .944$) but still captured the form of the data well.

With these fits we conducted three analyses. The first two compared the effect of degradation within each presentation condition (blocked and interleaved). The third compared the difference between 15-channel and 4-channel vocoding across the presentation conditions (see Table 1 for full results).

Table 1. *Results of timeseries analyses for Experiment 1 by word type (Target, Cohort) and level of degradation.*

Comparison	BDOTS output			
	Significant time window	Direction of effect	ρ	α
<i>Target</i>				
Blocked 15 vs 4	436-2000	15 > 4	.9944	.0025
Interleaved 15 vs 4	432-2000	15 > 4	.9941	.0023
(15-4) $\times$ Condition	904-1512	Blocked > Interleaved	.9994	.0134
<i>Cohort</i>				
Blocked 15 vs 4	436-732	15 > 4	.9930	.0019
	816-2000	4 > 15		
Interleaved 15 vs 4	412-708	15 > 4	.9872	.0011
	752-2000	4 > 15		
(15-4) $\times$ Condition	n.s.	n.s.	.9987	.0082

The first two analyses found a significant effect of degradation on target fixations from 436 to 2000 ms post word onset in the blocked condition (Figure 3A) and from 432 to 2000 ms in the interleaved condition (Figure 3B). These results are consistent with prior findings indicating that when speech input is highly degraded looks to targets begin later and do not reach the same asymptote.

Figure 3. Proportion of fixations to target over time as a function of degradation in A) blocked condition, B) interleaved condition. C) The difference in proportion of looks to the target in 15-channel versus 4-channel conditions by blocking condition.

Next, we asked whether the size of the advantage for 15-channel vocoding over 4-channel differed between blocking conditions. As Figure 1 and 2 suggest, any differences are likely to be small. To do this we computed the magnitude of the difference between the 15-channel and 4-channel conditions at each time. Here, a larger difference represents more separable patterns of fixations between the two levels of degradation; this may suggest the ability to more fully adapt to the input. Figure 3C shows these difference curves and suggests slightly less effect of degradation in the interleaved conditions.

These difference curves were analyzed in BDOTS using the difference of differences option. We found that somewhat late in processing, from 904 to 1512 ms, the blocked condition

showed a larger difference between vocoding conditions than did the interleaved condition (Figure 3C). This suggests that while the overall profile of target looks is similar, some aspect of interleaving impacts the degree to which participants can alter lexical processing.

Cohort fixations. Cohort fixations were fit with a six-parameter asymmetric Gaussian function. The six parameters included the peak height of the looks to the cohort, the timing of this peak, the variance for the left side normal distribution (essentially an onset slope), the variance for the right side normal distribution (essentially an offset slope), the baseline level of looks for the left side distribution, and the baseline level of looks for the right side distribution.

A total of 104 curves were fit (2/participant, for 4-channel and 15-channel vocoding). Of these, 63 of the fits were good with AR1 correlation ($R^2 > .95$), 1 fit was good without AR1, 32 fits were reasonable with AR1 ($.8 < R^2 < .95$), 5 fits were reasonable without AR1, two fits were relatively poor with AR1 ($R^2 < .8$), and 1 curve was not able to be fit due having multiple defined peaks over time. We attempted multiple refits and visually inspected these poor fits and determined that despite the lower R^2 value the fits could not be improved and reasonably characterized the underlying data.

As with the target data, three analyses were conducted. The first two examined the difference between levels of degradation within each level of presentation (blocked and interleaved). The third compared the difference between 15-channel and 4-channel vocoding across the presentation conditions (see Table 1 for full results).

In both the blocked and the interleaved conditions, cohorts showed higher activation early in processing in the 15-channel condition than the 4-channel condition (Blocked: 436-732 ms; Figure 4A; Interleaved: 412-708 ms; Figure 4B). Later in the trial, however, in both the blocked (816-2000 ms) and the interleaved (752-2000 ms) conditions, cohort activation was

preserved more highly in the 4-channel condition. The early suppression of the cohort competitor in 4-channel (relative to 15-channel) vocoded speech is consistent with prior research showing a “wait-and-see” profile when listeners process highly degraded input. The preserved cohort activation late in the trial is more consistent with sustained competitor activation, however, which was not previously observed in highly degraded input.

Figure 4. Proportion of looks to cohort item over time by level of degradation for A) blocked condition, B) interleaved condition. C) The difference in proportion of looks to the cohort in 15-channel versus 4-channel conditions by presentation condition.

As observed with target fixations, the patterns across blocked and interleaved conditions look very similar. Again, we computed difference curves between 4- and 15-channel conditions and compared these between the blocked versus interleaved conditions. Unlike the what was

observed for targets, there were no time points at which the blocked difference between 4- and 15-channel conditions differed statistically from the interleaved differences (Figure 4C).

Rhyme fixations. We planned to analyze rhyme fixations similarly to the cohort fixations. However, rhymes fixations, were not fittable for most participants. Instead, alternative analyses are presented in the supplemental material, and similarly showed no effects of blocking.

Discussion

The results of Experiment 1 are broadly consistent with previous findings that when speech input is highly degraded listeners adopt a “wait-and-see” profile of lexical activation (McMurray et al., 2017). When listeners heard 4-channel vocoded speech there was a pronounced delay in target activation and a corresponding decrease in peak looks to the target (relative to 15-channel). This appeared as a roughly 100 msec delay (degradation conditions showed a 112 ms difference in crossover for blocked presentation and 94 ms for interleaved). Cohorts showed a similar “wait-and-see” patterns of activation early in processing, as evidenced by the decreased looks to cohorts in the 4-channel noise vocoded speech conditions.

Somewhat unexpected, however, was the increase in cohort activation late in the trial for the 4-channel vocoded stimuli (seen in both blocked and interleaved conditions). This suggests that listeners may also be sustaining competitor activation to increase their ability to recover from misperceptions. There is recent evidence that CI users may also demonstrate both “wait-and-see” and sustained activation profiles (Smith & McMurray, submitted). Listeners could also potentially be committing less fully to the target which would allow all other items to appear more active (even the phonologically unrelated item). This would achieve the same goal of recovering more quickly in the event of a misperception. The relatively low accuracy in the 4-

channel condition would certainly suggest that this could be an adaptive strategy.

Interleaving levels of degradation randomly did not prevent participants from exhibiting the typical patterns of behavior consistent with the “wait-and-see” or sustained competitor activation profiles typical of 4 and 15-channel vocoded speech. Nonetheless a small effect of blocking was observed: the size of the difference between 4- and 15-channel target fixations was reduced with interleaved presentation compared to blocked. This was in the predicted direction, and it suggests that as processing proceeds, participants were more fully able to slow themselves (or delay commitment) when the level of degradation was relatively consistent across trials. Given the speed and regularity of target fixation patterns when listeners hear speech in quiet it may be easiest to detect small benefits across relatively brief exposure (240 trials) to highly degraded speech in the target time course.

This effect, while significant, was small and was not observed for the competitors. We see two possible explanations. First, differences between presentation condition may have been obscured by the fact that even in the blocked condition listeners had to process two different types of speech (and switched between the two types across four blocks of exposure). This was a necessary element of the design as we wanted both groups to have within-subject comparisons of 4- and 15-channel degradation. However, the overall effect of switching between types of speech might be more disruptive than we had predicted even in the blocked condition. After the first 120 trials, participants become aware that there is a second type of degraded speech that they will have to process. After the second set of 120 trials, participants switch back to the original level of degradation and are now aware that they will be required to switch between levels of difficulty. This could lead to participants maintaining two processing modes as they know on each trial, one or the other may be more beneficial. If this were the case, it would explain the

similar time course patterns between the presentation conditions but would not rule out learning as the explanation for why participants adopt the “wait-and-see” strategy.

Second, listeners in the interleaved condition may have been more capable of rapidly adapting to the various levels of degradation than we had anticipated. These participants may have been able to track both levels of degradation and adapt to them over time and then rapidly switch between the two modes of processing as they heard the first parts of the word. This might explain why the advantage for blocking (in the difference of differences analysis) emerged quite late in the timecourse of processing. If this is the case, the previous trial that participants experienced in the interleaved condition might have a large impact on the current trial.

To assess this, we next performed a set of exploratory analyses on just the interleaving condition. These asked if there is an effect of the previous trial’s level of degradation on lexical processing in the current trial. There are several possibilities. First, participants in the interleaved condition could “carry over” the profile from the previous trial. If this were the case, we would expect that when the previous trial matches the current trial lexical competition would look even more incremental on 15-channel trials and even more delayed on 4-channel trials. Second, participants could experience a cost for switching between degradation levels, and they may be delayed any time there is a mismatch between the previous and the current trial. Third, and finally, there may be no effect of prior trial which would suggest that the differences between 4- and 15-channel trials across the condition are driven by bottom-up signal quality differences alone. This third option seems particularly unlikely given the small, but significant, effect of blocking, but it offers a form of converging evidence for these findings.

Effects of Prior Trials

Given that the effects of interleaving were only observed in target fixations (the difference between 4- and 15-channel vocoding), these analyses examined the effects of prior trial match or mismatch on target fixations in the interleaving condition. We first split the data of the participants in this condition based on whether the prior trial matched or mismatched the current trial's level of degradation. We then analyzed the effects of prior trial match on target fixations separately for 4-channel and 15-channel trials.

As can be seen in Figure 5, the effect of switching between levels of degradation is most clearly evident when the current trial used 4-channel vocoded speech. Here, carryover predicts that looks to the target should show larger delays when the previous trial matched (was also 4-channel vocoded), and switch costs predicts larger delays when the previous trial mismatched. As Figure 5A shows, in 4-channel presentation there was an early and persistent large decrease in target activation if the previous trial was 15-channel – a switch cost. A BDOTS analysis comparing the effect of prior trial match on only 4-channel vocoding showed a significant difference from 684 to 2000 ms (see Table 2; average increase: .0483).

Table 2. *Results of exploratory timeseries analyses for Experiment 1 by level of degradation at match/mismatch of previous trial*

Contrast	Significant time window	Direction of effect	σ	α^*
<i>Target</i>				
15 Match vs Mismatch	824-2000	Mismatch > Match	.9993	.0124
4 Match vs Mismatch	684-2000	Match > Mismatch	.9984	.0073
Match Advantage	700-2000	4-ch > 15-ch	.9979	.0056

Figure 5. Proportion of fixations to the target over time based on status of previous trial when the current trial was A) 4-channel vocoding, B) 15-channel vocoding. C) Proportion difference between previous trial matches vs mismatches when the current trial was 4-channel or 15-channel noise vocoding.

In contrast, Figure 5B shows that when processing relatively intelligible 15-channel vocoded speech, we found a slightly later and smaller *increase* in target activation if the previous channel was 4-channel instead of 15-channel (824-2000ms; average increase: .0182; see Table 2 for full results). When processing 15-channel vocoded speech, carryover predicts that target fixations should be faster if the previous trial was a matching trial (also 15-channel). The same is predicted by a switch cost. This small benefit from having just processed a difficult 4-channel trial when now processing an easier trial is not consistent with either of our initial hypotheses.

To confirm this match advantage for 4-channel trials we conducted a difference curve

analysis as described above (Figure 5C). Trials involving highly degraded input showed a distinctly larger match advantage from 700 to 2000 ms into the trial compared to trials on which speech was more intelligible. As is also apparent from this analysis (Figure 5C) the unexpected mismatch benefit for 15 channels (the blue curve) is substantially smaller than the clear switch cost observed in 4-channel vocoding (the red curve).

Discussion. It appears that participants experience a cost when switching from relatively easy processing to more difficult processing, as seen in the decrease in target fixations when the current trial is 4-channel and the previous trial was 15-channel. This is not a “carry over” effect. If it were, we would expect 4-channel trials to show slower or lower target fixations when the previous trial matched; we found the opposite. Processing was harder when the level of degradation switched. A carryover effect also predicts slower processing on 15-channel trials when the previous trial mismatched (4-channel). But here, too, we find the opposite effect. However, here the effect is not consistent with a simple switch cost. Rather, processing is unexpectedly faster when the prior trial was 4-channel vocoded – which both mismatches from the current trial and predicts the wrong carryover effect.

Participants have a lifetime of experience processing relatively intelligible speech in which the spectral cues are preserved, and they have only a very limited amount of experience to processing noise vocoded speech. Thus, it makes some sense that the cost of switching is more readily apparent when the current trial involves 4-channel vocoded speech. On these trials, participants may need cognitive resources to adopt a more appropriate manner for lexical access. When the current trial involves 15-channel noise vocoded speech there is likely less need to alter lexical processing (compared to typical speech) as the distortion is minimal. This could explain why switch costs were only present on the 4-channel trials. We return to the much smaller and

unexpected effects on the 15-channel in the General Discussion.

These switch costs could be based on some cognitive engagement that attempts to alter lexical processing. Alternatively, they may also reflect some refractory period inherent in processing degraded input; that is low level auditory grouping or feature detection methods just cannot change fast enough to respond to the new input. This sort of refractory period or delayed adaptation would be likely fairly low level, and not based on higher level cognitive expectations.

These can be disentangled by providing listeners with non-auditory cues that could allow them to make the necessary adjustments in advance of the speech, potentially alleviating this cost. In Experiment 1, the only way participants in the interleaved condition could tell what level of degradation they would hear on a given trial was to hear it directly in the stimulus. In this case, they must adapt quickly – during the first few hundred msec of the word for this to have any benefit. This did not impact their ability to learn to cope with the signal (as evidenced by similar accuracy levels and similar time course effects in terms of lexical activation). However, these exploratory analyses suggest that on a trial-to-trial level the unpredictability of the signal could impact lexical competition. In Experiment 2 we thus ask if a simple visual cue can alleviate this “switch cost” when levels of degradation are randomly interleaved.

Experiment 2

Methods

Participants. Thirty monolingual English speakers participated in this experiment. All participants reported having normal or corrected-to-normal vision and normal hearing. Participants were students at the University of Iowa and received course credit as compensation for participating in the experiment. All participants provided informed consent according to

Institutional Review Board approved protocols for this study. Two participants were excluded from analysis due to technical issues with data collection, one participant was excluded due to poor calibration, and one participant was excluded due to low overall patterns of looking throughout the experiment. This left 26 participants for all reported analyses.

Design. This experiment used the same 30 item sets used in Experiment 1 (120 total words). The only experimental factor was the number of channels of vocoding (difficulty), was manipulated within-subjects. All participants heard 4-channel vocoding on half of the trials and 15-channels of noise vocoding on the other half, randomly interleaved.

Critically, a visual cue was presented prior to the onset of each auditory stimulus to indicate the difficulty on each trial. This made it possible to predict the level of vocoding as the experiment proceeded despite the random nature of the interleaving.

Stimuli. Auditory and visual stimuli were the same as Experiment 1.

Procedure. The procedure for this experiment was largely the same as that of Experiment 1. On each trial, four images were displayed at each corner of the screen and a fixation circle was displayed at the center. In this experiment, the color of this fixation circle varied based on the level of difficulty in a given trial (blue for 15-channel, red for 4-channel). After 500 ms the circle changed to a lighter shade of the original color and participants clicked on it to begin the trial. Participants were told that the color of the circle would indicate the relative difficulty of each trial but were not given any specific information about the vocoding. They were warned during instructions that the speech they would hear would sound distorted and that they should make their best guess if they were unsure of what they heard.

Eye-tracking recording and processing. The same equipment and processing techniques were used for this experiment as were used in Experiment 1.

Results

This experiment was designed to be compared to the interleaved condition of Experiment 1. We conducted three primary sets of analyses. The first examined the accuracy of the mouse-click response as a function of level of degradation (4-channel or 15-channel vocoding). We then turn to the analysis of fixations, which focused on the time course of target fixations (as this is where the effect of blocking and interleaving was observed). The second analysis examined fixations across levels of degradation and whether the previous trial matched the current trial's level of degradation within Experiment 2. Finally, we directly compared this experiment to Experiment 1 to determine if the visual cue reduced the effect of prior trial mismatch.

Accuracy. Not surprisingly, participants showed much higher accuracy with 15-channel vocoded speech (96.96% accuracy) than 4-channel noise (82.85% accuracy), $t(26) = 14.61$, $p < .001$ (logit transformed). These results are consistent with the results of Experiment 1.

Time course of fixations. Figure 6A shows looks to the target over time in both 4- and 15- channel conditions. The pattern of fixations to the target in these conditions was consistent with Experiment 1. Target fixations were again analyzed using the BDOTS. We first assessed the difference between 4- and 15- channel degradation to confirm that the pattern was similar to

Figure 6. A) Proportion of looks to target over time as a function of level of degradation. B) Proportion of looks to target over time as a function of previous trial match or mismatch for 4-channel trials. C) Proportion of looks to target over time as a function of previous trial match or mismatch for 15-channel trials. D) Difference curves between match and mismatch conditions over time by level of degradation of current trial.

Experiment 1. A total of 52 curves were fit (two per participant, one for 4-channel vocoding and one for 15-channel vocoding). Of these, all had good fits ($R^2 > .95$) with AR1. As expected, there was a clear advantage for the 15-channel condition over the 4-channel condition which emerged

from 464 ms to 2000 ms (Figure 6A; see Table 3 for full results).

Next, we divided the data based on the status of the previous trial. As can be seen in Figure 6, the effect of switching between levels of degradation is again most clearly evident when the current trial used 4-channel vocoded speech (Figure 6B) than 15-channel (Figure 6C). The visual cue was clearly not sufficient to completely eliminate the match advantage when participants processed more than one 4-channel trial in a row. Nonetheless the effect also appeared substantially reduced (compare to Figure 5A).

For BDOTs, the data were split by the prior trial and refit. This led to a total of 104 curves fit (four curves per participant). Of these, 100 had good fits ($R^2 > .95$) with AR1, while an additional 3 had good fits without AR1 and the remaining one fit was acceptable at $R^2 = .937$. Refitting was attempted but did not improve fit quality for the single fit below .95, though the fitted curve still captured the data well. With these fits, we conducted three analyses. The first two compared the effects of previous trial match across 4-channel and 15-channel vocoding conditions. The third compared the difference between match and mismatch trials between degradation conditions. Finally, we compared the two experiments to ask if the visual cue reduced the magnitude of the switch costs.

Table 3. *Results of timeseries analyses for Experiment 2 by level of degradation and match condition.*

Comparison	Significant time window	Direction of effect	ρ	α^*
<i>Target</i>				
15 vs 4	464-2000	15 > 4	.9952	.0028
4 Match vs Mismatch	800-2000	Match > Mismatch	.9987	.0201
15 Match vs Mismatch	628-1048	Mismatch > Match	.9993	.0134
Match Advantage	644-2000	4 > 15	.9997	.0191
<i>Cross Experiment</i>				
4 Match Advantage	872-1384	No Context	.9999	.0274
15 Match Advantage	1216-2000	Context	.9990	.0100

The BDOTS analysis comparing the effect of prior trial on target activation showed a significant difference between match and mismatch when the current trial was 4-channel from 800 to 2000 ms (see Table 3; average increase: .0297). This advantage does not persist as long as in Experiment 1 (1200 ms in Experiment 2 vs. 1316 ms in Experiment 1), nor was it as large.

Figure 6C shows that when processing the more intelligible speech (15-channel) there was still an advantage when the previous trial was 4-channel instead of 15-channel as observed in exploratory analyses of Experiment 1. This advantage lasted from 628 to 1048 ms (see Table 3; average increase: .0155). Once again, adding the visual cue did not eliminate the advantage of previously having processed a difficult trial when the current trial is relatively easy. However, unlike in the exploratory analyses, this advantage did not persist until the end of the trial suggesting that the effect did not affect the participants' ability to resolve competition.

We conducted a difference curve analyses to compare the size of the match advantage for 4-channel trials compared to 15-channel trials. Just as before, trials involving 4-channel speech showed a distinctly larger match advantage than trials involving 15-channel speech and this difference persisted from 644 to 2000 ms (Figure 6D). While a visual cue led to a numerically smaller advantage within the 4-channel trials and a less persistent advantage in 15-channel trials, the effect within 4-channel trials remains significantly larger than in 15-channel trials.

Comparison across experiments. To determine whether the visual cue impacted the switch cost, we conducted two final analyses. Each focused on single level of degradation and compared the difference curves of match and mismatch trials across the two experiments (visual context or no context). This was done separately for each level of degradation. Figure 7A shows the match advantage for the 4-channel trials. It shows a much larger effect of prior trial match in 4-channel trials when there was no visual context (Experiment 1) than when visual context was

provided (Experiment 2). This difference persisted from 872 to 1384 ms.

In contrast, in Figure 7B it is evident that the match advantage was larger when there was visual context and that this difference persisted from 1216 to 2000 ms (Table 3 for full results).

Figure 7. Difference in proportion of looks to target between match and mismatch trials over time as a function of experiment (context: Experiment 2, no context: Experiment 1) when the current trial was A) 4-channel vocoding or B) 15-channel vocoding.

This larger “advantage” when visual context is provided in effect reduces the difference given that the match “advantage” in our exploratory analyses had a negative effect (mismatching trials had higher looks during significant regions).

Discussion

Experiment 2 asked whether the seeming switch cost during interleaved trials in Experiment 1 was the result of a cognitive adaptation to the change in level of degradation from trial to trial. In Experiment 1 we found clear switch costs when the current trial was highly degraded (4-channel vocoded). In Experiment 2, a simple visual cue presented for 500 ms was sufficient to significantly reduce the cost of switching from intelligible speech on the prior trial to much more degraded speech. There was still a switch cost, though it was reduced in

magnitude and duration during the middle of processing (as seen in the difference of differences analysis, Figure 7A). This supports that hypothesis that the switch cost observed in Experiment 1 was at least partially driven by cognitive expectations and can be in part ameliorated by them.

Adding this visual cue also had the effect of reducing the unexpected mismatch benefit when the current trial was 15-channel vocoded. The average size of the effect was similar between Experiment 1 (Figure 5B) and Experiment 2 (Figure 6B). However, the effect was far less persistent and did not impact looks late in the trial. Nonetheless, the fact that this effect replicated suggests that the unexpected effect observed in Experiment 1 is not noise.

One potential explanation for this mismatch benefit would be that the prior 4-channel trial led participants to engage more effort while processing and this increased effort continued to be engaged into the current trial. This was clearly the case in Experiment 1, and to a lesser extent in Experiment 2. However, Experiment 2 suggests that when a reliable visual cue was provided, participants knew that the current 15-channel trial was not going to require the increased effort and thus the effect did not persist until late in the trial, even as they could not eliminate this carry over of effort entirely.

Zhang and Samuel (2018) offer evidence that cognitive load impacts the late resolution of competition but not necessarily the speed of initial access. The kind of non-linguistic cue to the quality of the upcoming speech in this experiment could help lower cognitive load, generally. This would explain the smaller match-mismatch differences in Experiment 2. Normally interleaving trial types should make adapting to the level of degradation more difficult as the level of degradation is randomly determined on any given trial. The results of this experiment suggest that multiple cognitive factors may impact lexical processing.

General Discussion

This study investigated the potential causes of changes in lexical processing when speech is highly degraded. To briefly summarize the main findings, Experiment 1 presented two levels of degradation in either a blocked or interleaved schedule. We found that in both conditions, listeners exhibited a “wait-and-see” profile of activation when hearing 4-channel vocoded speech. Interleaving the two levels of degradation moderated this effect on target fixations, with a smaller effect for the interleaved condition. Exploratory analyses further suggested that switching between levels of degradation impacts processing in-the-moment; the level of degradation of a previous trial impacts processing the current trial. In Experiment 2 a simple visual cue was added to indicate the relative level of difficulty on each trial. This reduced, but did not eliminate, the differences in processing when the prior trial mismatched the current trial.

We discuss each of these major findings in turn.

Changes in Lexical Processing

The results across both experiments replicate the prior findings that 4-channel noise vocoded speech leads listeners to demonstrate a “wait-and-see” profile of lexical activation. We observed large delays in fixations to targets in both experiments. In Experiment 1 we also saw reduced peak cohort fixations, and a potential increase in late rhyme activation (see Supplement). Both of these are consistent with a “wait-and-see” profile. This replication adds to the evidence that when the speech signal is missing information, listeners delay lexical processing until more of the signal has been received (see also Hendrickson et al., 2020; McMurray et al., 2017). It may be the case that some critical amount of information (broadly speaking) is required to initiate lexical access. When the signal is highly degraded more of the signal is required to reach

this amount of identifying information.

It is not currently clear if this “wait-and-see” approach is beneficial. This type of delay may be adaptive given the difficulty in recognizing 4-channel noise vocoded speech. Delaying lexical access allows the lexical system to accumulate more information (e.g., additional phonemes) prior to making a commitment to a particular word. This would reduce the likelihood that a single misperceived phoneme derails word recognition. In addition, the lower commitment to a specific lexical candidate (as reflected in the lower peak looks to targets) would allow for easier recovery when misperceptions occur (McMurray et al., 2019), consistent with sustained competitor activation. The previous work that had found evidence of the “wait-and-see” approach did not observe simultaneous sustained competitor activation (McMurray et al., 2017), so this is somewhat surprising, but these two differences may clearly work in concert.

This “wait-and-see” approach is not without drawbacks, however, as delaying lexical access means slower processing. The main benefit of immediate and incremental processing is to make early inferences about the intended speech target. This allows listeners to map speech onto meaning quickly. If “wait-and-see” is a useful way to cope with highly degraded input, however, it is encouraging that interleaving does not disrupt listeners’ ability to take this approach.

Adaptation

The primary goal of this study was to identify how individuals adapt to process highly degraded spectral input. The wait and see profile could be an automatic consequence of receiving poor input, or it could be the result of adaptations made to parameters of the lexical system. To test whether these differences are strictly caused by differences in the bottom-up input, Experiment 1 presented two levels of noise vocoded speech in either a blocked or interleaved

schedule. If the previously observed “wait-and-see” pattern was the result of cognitive adaptations listeners should have shown smaller differences in lexical processing between the two levels of vocoding in the interleaved condition which should have made learning more difficult. If, instead, these differences are purely driven by the bottom-up input, blocked and interleaved conditions should show similar effects of degradation level.

Contrary to the strongest prediction that interleaving would prevent listeners from showing differences 4- and 15-channel vocoding, in both blocked and interleaved conditions there were large effects of vocoding level. Interleaving levels of degradation did not prevent listeners from displaying the typical “wait-and-see” pattern of lexical access. Unsurprisingly, the quality of the bottom-up signal plays a large role in promoting a “wait-and-see” pattern.

However, lexical processing is not solely driven by the bottom-up input. Interleaving had a significant impact on the difference in target fixations between the 4- and 15-channel conditions. Participants in the blocked condition showed a larger difference in target fixations between the vocoding conditions than participants in the interleaved condition. This difference was relatively small but persisted from 904 to 1512 ms during processing. This effect indicates that some form of adaptation or learning is involved in processing degraded speech and that people appear to be able to maintain two levels of degradation simultaneously. Interleaving did not prevent a “wait-and-see” profile but it did interfere with how effectively listeners could adopt the two strategies within a single experiment.

While the difference between blocked and interleaved presentations was significant and persisted for 608 ms, it was also small. The obvious reason for this small effect may simply be that the bottom-up signal is a larger factor. However, there are two additional reasons that the differences may have been small. First, learning may have been slower than expected, and the

blocked participants were not able to reach asymptotic levels of performance. Prior work with vocoded speech has required several sessions (or immediate feedback) to get participants to adapt to spectrally degraded input (Hervais-Adelman et al., 2008; Shannon et al., 1995). Second, learning could have been faster and more robust than expected. That is, it is possible the interleaved participants may have been able to learn as effectively as the blocked participants and then rapidly switch back and forth between the two strategies (the wait and see for 4-channel vocoding and the more incremental mode for 15). To examine this, we analyzed the effects of switching between levels of degradation in the interleaved condition.

Switching Costs and Effort

We hypothesized that if that learning was occurring rapidly in the interleaved condition, listeners may show a carryover effect when the previous trial matched the level of degradation of the current trial. If there was a carryover effect, lexical access patterns would become more immediate across two 15-channel trials or more delayed across two 4-channel trials. However, a contrasting prediction was that interleaving could impose a switch cost based on the match of the quality of the input from trial to trial. If this were the case, listeners would be faster when the previous trial matched the current level of degradation and slower when it did not match.

Our exploratory analyses of the effect of the prior trial revealed that the previous trial had an impact lexical processing in the current trial. This impact was largest when the current trial was highly degraded, but it was significant for both 4- and 15-channel vocoding trials. Critically, the effects did not reflect a carryover effect, suggesting that the overall effect of interleaving levels of degradation was not due to rapid learning and trial-to-trial updating.

Instead, we found a switch cost in the highly degraded (4-channel vocoding) trials. When

the current trial was highly degraded, participants were faster to look to the target and had higher peak looks if the prior trial was also highly degraded. This suggests that switching from relatively easy and rapid lexical processing (when the previous trial was 15-channel) comes at a cost. The results of Experiment 2 indicate that this cost is not purely a low-level and autonomous property of the auditory system; it can be attenuated by a simple visual cue. This fits with evidence that when listeners are under cognitive load, they exhibit slower lexical access (Hadar, Skrzypek, Wingfield, & Ben-David, 2016); this suggests that switching between levels of degradation may function similarly to other forms of load.

However, when the current trial was less degraded (15-channel vocoded), participants were faster to look to the target and had higher peak looks if the previous trial was highly degraded (mismatched). This suggests that switching from difficult trials to more incremental processing does not exert a cost (unlike the converse), and in fact offers a benefit. This may derive from a secondary effect: the level of effort engaged. Mounting research suggests that highly degraded speech requires more cognitive effort (Peelle, 2018), potentially in order to engage this “wait-and-see” mode of processing. Presumably, this effort serves to facilitate processing. We hypothesize here that effort may persist across trials; that is the engagement of effort may have its own time course of decay after a specific situation demanded effort. Given this, processing should be faster in 15-channel vocoded speech when preceded by the more difficult (more effort demanding) 4-channel. However, the converse may not be true since 15-channel speech may not engage any extra effort. Here only the switch cost remains.

The results of Experiment 2 show how these two factors fit together. The reduction of the switch costs in Experiment 2 is likely due to cognitive expectations which can impact the cost of switching between two processing modes. The remaining differences observed between

matching and mismatching trials in Experiment 2 may be the result of effort engaged on the previous trial. If effort on a previous trial leads to faster processing overall (4-channel on previous trial leads to faster processing regardless of current trial type) but switching leads to slower processing overall this could explain the pattern of results we observe here. It appears that the results of this experiment are explained by a combination of the cognitive expectations about upcoming level of degradation (which reduce the switch cost) and the level of effort engaged on the prior trial (which speeds processing).

The Cognitive Mechanisms of Adaptation

Adapting to process degraded speech involves some level of perceptual retuning. Individuals can adapt to processing vocoded speech and may particularly rely on lexical or semantic feedback to help shape this retuning process (Davis, Johnsrude, Hervais-Adelman, Taylor, & McGettigan, 2005; Hervais-Adelman et al., 2008). Listeners can also shift cue weightings when a primary cue to phoneme identity is less reliable (Kim et al., 2020; Winn, Chatterjee, & Idsardi, 2012). In our present experiment there was no explicit feedback and the amount of experience individual listeners had with the highly degraded speech was quite limited (2 repetitions of each of 120 words). Thus, the effect of perceptual retuning was likely minimal. Nevertheless, the closed set nature of the VWP task may have allowed for lexical guidance of perceptual retuning during early trials when the 4-channel speech would have been novel. Beyond perceptual retuning, however, we found strong evidence of changes in lexical processing that were explained by more than just the bottom-up peripheral signal quality.

The results across these two experiments indicate that the differences in lexical competition in the face of highly degraded speech (McMurray et al., 2017) appear to involve at

least three cognitive mechanisms. First, the fact that we observed a small but significant effect of interleaving supports the hypothesis that coping with degraded speech requires some amount of learning to proceed efficiently. Second, the fact that switch costs are observed in interleaved processing and that these costs are reduced when visual cues are provided suggests that expectations can engage cognitive control to mitigate cost of switching between processing modes. Listeners are able to prepare for the type of processing that will be required to cope with the upcoming signal. Finally, when processing requirements have recently engaged a large amount of effort the next trial seems to receive a benefit due to the previous level of difficulty, regardless of current level of difficulty (as in Hendrickson et al., 2020). While the bottom-up signal is clearly an important factor in determining if “wait-and-see” processing occurs, effort and expectations can impact how effectively this processing is adopted.

Implications for Clinical Hearing Science

In addition to informing how changes in lexical processing may be adopted generally, these experiments also provide useful information when considering CI users, for whom vocoding is often used as a proxy for their perceptual challenges. Different processor settings can be configured to be used in a variety of listening situations (e.g., a quiet room or a noisy environment) and the results of these experiments suggest that switching between these processing modes may require some cognitive adaptation and effortful processing. If the change in processor settings provides enough of a benefit this would be helpful for CI users in terms of adapting to challenging listening situations. However, if the benefit is minimal, the effort to adapt to the change in the input received might lead to CI users ignoring these additional settings even if they can yield benefits to speech recognition (indeed audiologists report that CI users

often adopt a “set it and forget it” strategy—perhaps in part to avoid the switch costs).

Similarly, many new CI users with residual acoustic hearing or with single side of deafness report turning off their CI in a variety of listening scenarios and relying solely on their acoustic hearing ear. Our results suggest that this would lead the lexical system to adapting differently than if the CI were left on. This could have long-term adaptation implications if CI users are frequently varying their input quality (turning the CI off frequently). It should be noted, however, that the results of Experiment 2 suggest that as long as these changes are predictable the cost of switching between levels of input quality are minimized.

Finally, our results imply that the amount of effort expended in processing incoming speech is not solely dependent on the current level of difficulty. The amount of effort invested in processing seems to carry over from trial to trial suggesting a slower adaptation. While our analyses only examined the effects of the previous trial, it is plausible that longer-lasting effects also occur. If so, CI users who are in a challenging listening situation (a noisy environment) for long periods of time may continue to engage additional effort after leaving that environment (even if only for a short time). This may not yield additional benefits for speech recognition any longer but would continue to expend cognitive resources leading to fatigue or dissatisfaction.

Conclusions

The quality of the bottom up signal is the primary driving force in determining which type of processing (incremental or wait-and-see) is engaged during lexical access. However, these results show that listeners also rely on cognitive expectations to adopt a processing approach more fully. Randomly interleaving levels of degradation revealed a cost to switching between the two approaches as well as the potential longer-term carry over of effort in

processing. Our results suggest that several cognitive processes may impact lexical access in challenging listening conditions.

Acknowledgements

Thanks to Sarah Colby and Keith Apfelbaum for feedback on the design and interpretation of this project. Thanks to Jamie Klein-Packard for help with recruitment and running of participants.

Declarations

Funding

This research was supported by National Institute of Health Grants DC008089 awarded to Bob McMurray, and DC000242 to awarded to Bob McMurray and Bruce Gantz.

Conflicts of Interest

We have no conflicts of interest, financial or non-financial, to disclose.

Ethics Approval

Approval was obtained from the Institutional Review Board of the University of Iowa (IRB ID# 200409711).

Consent to Participate

Informed consent was obtained from all individual participants included in this study.

Consent for Publication

Not applicable.

Availability of Data and Materials

The datasets generated during the current study are available from the corresponding author on reasonable request.

Code Availability

Not applicable.

Open Practices Statement

The datasets generated during the current study and materials used are available from the corresponding author on reasonable request. None of the experiments were preregistered.

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S1. Analyses of Rhymes

As we described in the main text, CI user's fixations to rhymes could not be analyzed in the same manner as cohorts. Many of the individual rhyme curves were not able to be fit properly using BDOTS due to low patterns of looking or fixation patterns that did not conform to the typical, and group level, double Gaussian shape. The fits that were obtained were generally good, but there were not enough successful fits to perform bootstrapping and thus the BDOTS analysis was abandoned and we performed an analysis that borrows from many aspects of BDOTS. We first smoothed the raw rhyme fixations for each participant and each level of degradation using a 48 ms triangular window. We then computed *t*-tests at each time point, calculated the autocorrelation among these *t*-tests, and then used this correlation to calculate a corrected alpha level – just as in BDOTS. These analyses are less sensitive because we were unable to perform a bootstrapping procedure as in typical BDOTS analyses. Because this was not our initial planned analysis it may be treated as exploratory, though the results are consistent with the findings for cohort items using BDOTS analysis.

As can be seen in Figure S1A, B the results of the rhyme analysis, like that of the cohort analysis, seem to show similar patterns between the blocked and interleaved conditions. Rhymes show higher activation late in the trial in the 4-channel condition relative to the 15-channel condition (Blocked: 796-2000 ms; Figure S1A; Interleaved: 788-2000 ms; Figure S1B). This increased late activation of rhymes is somewhat consistent with a “wait-and-see” pattern (though this is harder to identify because the peak activation amounts are not particularly increased). In addition, the persistence of the activation is consistent with sustained competitor activation. We next performed a difference of difference analysis just as we did with cohorts (without the bootstrapping procedure, as described above). Just as with cohorts, there were no significant

regions in the difference of differences analysis suggesting that the blocked versus interleaved effect observed in target activation is either not present in competitor activation or that competitor differences are not reliable enough to detect this small difference.

Figure S1. Proportion of looks to rhyme item over time by level of degradation for A) blocked condition, B) interleaved condition. C) The difference in proportion of looks to the cohort in 15-channel versus 4-channel conditions by presentation condition.