**Lexical Access Changes Based on Listener Needs:
Real-Time Word Recognition in Continuous Speech in Cochlear Implant Users**

Running Head: Lexical Access in Continuous Speech

Francis X. Smith¹ and Bob McMurray^{1,2}

¹Dept. of Psychological and Brain Sciences

²Dept. of Otolaryngology
University of Iowa

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All correspondence should be addressed to:

Francis X. Smith, Department of Psychological and Brain Sciences, 255 PBSB, University of Iowa, Iowa City, IA 52242, USA. E-mail: francis-smith@uiowa.edu

Abstract

Objectives. A key challenge in word recognition is the temporary ambiguity created by the fact that speech unfolds over time. In normal hearing (NH) listeners, this temporary ambiguity is resolved through incremental processing and competition among lexical candidates. Post-lingually deafened cochlear implant (CI) users show similar incremental processing and competition but with slight delays. However, even brief delays could lead to drastic changes when compounded across multiple words in a phrase. This study asks whether words presented in non-informative continuous speech (a carrier phrase) are processed differently than in isolation and whether NH listeners and CI users exhibit different effects of a carrier phrase.

Design. In two Visual World Paradigm experiments, listeners heard words either in isolation or in non-informative carrier phrases (e.g., “*click on the...*”). Listeners selected the picture corresponding to the target word from among four items including the target word (e.g., *mustard*), a cohort competitor (e.g., *mustache*), a rhyme competitor (e.g., *custard*), and an unrelated item (e.g., *penguin*). Eye movements were tracked as an index of the relative activation of each lexical candidate as competition unfolds over the course of word recognition. Across both experiments, subjects included 43 post-lingually deafened CI users and 39 NH controls.

Results. Both CI users and the NH controls were accurate at recognizing the words both in continuous speech and in isolation. The time course of lexical activation (indexed by the fixations) differed substantially between groups. CI users were delayed in fixating the target relative to NH controls. Additionally, CI users showed less competition from cohorts than NH controls (even as previous studies have often report increased competition). However, CI users took longer to suppress the cohort and suppressed it less fully than the NH controls. For both CI users and NH controls, embedding words in carrier phrases led to more immediacy in lexical

access as observed by increases in cohort competition relative to when words were presented in isolation. However, CI users were not differentially affected by the carriers.

Conclusions. Unlike prior work, CI users appeared to exhibit “wait-and-see” strategy, in which lexical access is delayed to minimize early competition. However, they simultaneously sustain competitor activation late in the trial possibly to preserve flexibility. This hybrid profile has not been observed previously. When target words are heard in continuous speech, both CI users and NH controls more heavily weight early information. However, CI users (but not NH listeners) also commit less fully to the target, potentially keeping options open if they need to recover from a misperception. This mix of patterns reflects a lexical system that is extremely flexible and adapts to fit the needs of a listener.

Introduction

Speech recognition is challenging to explain even in ideal listening situations. The speech signal is variable between talkers, and even between productions from a single talker (Liberman & Cooper, 1967; McMurray & Jongman, 2011; Newman et al., 2001), and it varies due to speaking rate (Miller et al., 1986) and coarticulatory context (e.g., Daniloff & Moll, 1968). In addition, the signal unfolds over time, leading to periods of temporary ambiguity about the intended word. For example, as a listener hears a word like *sandal*, at onset (e.g., after hearing *san-*) the input is briefly consistent with many possible words like *sandal*, *Santa* and *sandwich*.

These challenges are more daunting when the signal is unreliable, as in cochlear implant (CI) users. Due to inherent limitations in the electrical properties of the CI, frequency resolution is profoundly reduced. While CI users generally fare well with speech perception, there is considerable variability in outcomes (Blamey et al., 2013; Gomaa et al., 2003). Variability in speech recognition performance in CI users is not fully explained by the auditory periphery. As a result, researchers have begun to examine cognitive processes that are harnessed to cope with ambiguity in every day (clear) speech in NH listeners that could be adapted to deal with increased ambiguity in CI users. This study focuses on the process of selecting words from a range of candidates as speech unfolds – lexical access. Experience with the CIs may alter this process because of the poorer reliability of their input (Farris-Trimble et al., 2014; McMurray et al., 2017), altering the competition mechanisms that underlie word-recognition.

Prior work has largely focused on words in isolation (Farris-Trimble et al., 2014; McMurray et al., 2017). But this process may change in several ways when words are embedded in phrases. Thus, the goal of this study is to better understand how this competition is altered in CI users when processing words in simple sentences.

Spoken Word Recognition

In normal hearing (NH) listeners, word recognition has been framed in terms of the problem of temporary ambiguity created by the fact that speech unfolds over time. It is generally agreed that NH listeners resolve this ambiguity via competition (Dahan & Magnuson, 2006; Hannagan et al., 2013; Marslen-Wilson, 1987; McClelland & Elman, 1986; Norris, 1994; Weber & Scharenborg, 2012; Zwitserlood, 1989). As soon as any input arrives, listeners partially activate multiple lexical items consistent with the signal. For example, while hearing the onset of *sandal* (*sa-*), they may consider *sandwich* and *sandbox*. Listeners remove items from consideration when they are no longer supported by the input (e.g., at *-al*, *sandbox* drops out), and may briefly (but partially) consider words that do not overlap at onset (e.g., *handle*, *shandy*) (Allopenna et al., 1998; Toscano et al., 2013). Thus, lexical processing begins immediately after any input, proceeds incrementally, and responds to new information immediately as it arrives.

One of the primary methods for investigating online word recognition is the Visual World Paradigm (VWP) (Tanenhaus et al., 1995). In a typical VWP experiment, participants hear a target word and see four pictures on the screen. The task is to click on the matching picture. The objects represent words that may be considered during processing (e.g., phonological competitors) or unrelated words. Participants' eye movements are tracked while they complete this task. To select a picture, participants must find it and plan a motor action, and this usually requires them to usually launch several eye movements. Because eye movements are launched while lexical processing is ongoing, the proportion of fixations to each object capture that word's degree of consideration at the point when each fixation is launched.

Typically, eye movements begin shortly after the onset of speech (~200 ms) and reflect

the earliest information in the signal heard. At word onset, if a participant hears *sandal*, they will fixate both the target (*sandal*), and pictures of words that overlap at onset (cohorts like *sandwich*). Rhymes (e.g., *candle*) receive fixations later in the trial. By about one second after word onset, listeners have generally fully committed to the target.

Several lines of evidence point to the idea that the lexical system is geared toward managing uncertainty about the intended word, which could help listeners deal with challenging listening scenarios (such as spectral degradation). First, competition is biased by word frequency (Dahan, Magnuson, & Tanenhaus, 2001; Marslen-Wilson, 1987), which could serve as a prior when the bottom-up input is insufficient. Second, words exert inhibition such that a partially active target word actively suppresses competitors (Dahan, Magnuson, Tanenhaus, et al., 2001; Luce & Pisoni, 1998). Inhibition could amplify weak differences in activation among candidates, which could be helpful in quickly suppressing residual activation of non-relevant lexical entries when the input is partially ambiguous. Third, the fact that both rhyme and anadrome competitors are active (Allopenna et al., 1998; Connine et al., 1993; Gregg et al., 2019; Toscano et al., 2013) indicates that the system considers words even after a disconfirming segment is heard. When input is unreliable this type of system could help recover from errors when one or more phonemes were misperceived. In this situation, one of the competitors (for the mispronounced input) are likely to be the target and could be quickly reactivated.

Thus, the dynamics of lexical access do not passively reflect the unfolding input. Rather, this competition process is flexible (and may even be tuned with training, Kapnoula & McMurray, 2016) and may be well suited to dealing with uncertainty. These dynamics might also adapt to help listeners in challenging situations, such as individuals with cochlear implants who receive spectrally degraded input that may be harder to recognize.

Cochlear Implants

CI users face additional forms of uncertainty beyond temporary ambiguity, as the auditory input is characterized by reduced information. The input that CI users receive preserves the temporal envelope of the speech signal, but otherwise is spectrally degraded because 1) the thousands of frequencies discriminable on the cochlea are collapsed to a small number of electrodes (with limited benefits for adding additional electrodes: Fishman, Shannon, & Slattery, 1997; Friesen, Shannon, Baskent, & Wang, 2001); and 2) current processing strategies do not preserve temporal fine structure and may ignore some frequencies entirely.

There is substantial variability in CI users' outcomes (Blamey et al., 2013; Gomaa et al., 2003), and even experienced CI users struggle in challenging listening situations (Armstrong et al., 1997; Hochberg et al., 1992). While much of this variation is due to differences in the fidelity of the signal (Blamey et al., 2013; Henry et al., 2005; Litvak et al., 2007), CI users may also differ in how they calibrate the way lexical competition unfolds to manage uncertainty.

Supporting this, studies with NH listeners have shown that lexical competition is affected by the reliability of the signal. Brouwer and Bradlow (2016) found that adding broadband noise increases competition of both cohorts and rhymes (see also Ben-David et al., 2011). This could in part be due to the fact that the cues discriminating the target and competitors are no longer as informative (e.g., spectral detail is lost). However, enhanced activation for competitors could help cope with greater uncertainty. That is, it could be beneficial to keep competing lexical candidates available to help recover from a misperception. In these studies, the fact that the target was noise-masked makes it difficult to isolate the effects of adaptation from the fact that poor input simply contains less information contrasting the target from competitors. Thus,

McQueen and Huettig (2012) added noise to carrier sentences but the target word was always clear. When the carrier sentence contained noise, listeners looked less to the cohort and looked more to a rhyme (implying that they were processing speech less immediately). This suggests that the expectation of difficulty alone can alter the dynamics of lexical competition¹.

The changes in the profile of competition differ between these studies: Huettig and McQueen show reduced cohort (but increased rhyme) fixations while Brouwer and Bradlow show across the board increases in competitor fixations. These differences may be due to differences in tasks, the type of noise and the level of uncertainty. Still, at the broadest level, these studies suggest the lexical system can be adapted when input is unreliable or uncertain.

CI users' long-term experience with challenging input may lead them to adapt lexical competition. Farris-Trimble et al. (2014) examined post-lingually deafened CI users in a VWP task. Relative to NH controls, CI users showed a slight delay in processing (about 70 milliseconds). The delay is likely a processing cost resulting from the decrease in signal quality, as it was also observed for NH controls hearing noise-vocoded speech. However, CI users also showed evidence of *sustained competitor activation*: cohorts and rhymes remained active longer (Farris-Trimble et al., 2014). This may be adaptive for coping with unreliable input quality (as in Brouwer and Bradlow, 2016), allowing greater flexibility for recovering after a misperception.

Since the signal quality is necessarily degraded in CI users, these changes may just be an automatic consequence of the poor input. McMurray et al. (2016) investigated this in a phoneme categorization task along with eye-tracking to gauge lexical competition. CI users showed more

¹ It is not clear whether this is beneficial to listeners or not. McQueen and Huettig (2012) did not include a target on the screen to gauge listeners' efficiency of recognizing the word. However, we now know that this profile of reduced cohort/increased rhyme fixations is consistent with a "wait and see" approach in which listeners delay lexical access until more information arrives (McMurray et al., 2017).

competitor fixations across all continua steps, which is consistent with the sustained competitor activation observed by Farris-Trimble et al. (2014). Importantly, after accounting for the ultimate categorization decision, both CI and NH listeners' fixations were equally sensitive to the degree of phonetic ambiguity of the auditory stimulus (indicated by the slope of the fixation response as a function of continuum step). This suggests that sustained competitor activation is unlikely to derive from the lack of ability to categorize acoustic input, as both groups were similarly sensitive to changes in VOT and frication spectrum.

Evidence that changes in lexical competition may be adaptive comes from a study examining the effects of mispronunciation. McMurray, Ellis, and Apfelbaum (2019) presented either onset or offset mispronunciations in a VWP experiment (e.g., *dog* mispronounced as *tog*) and examined the speed of fixating the target. CI users were *less* disrupted by onset mispronunciations than NH listeners. This is consistent with a strategy by which CI users slow down and keep competitors active so that they can recover when they discover a mistake (e.g., when they hear /g/, realize that *tog* is not a word, and must reactivate *dog*).

This sustained competitor activation profile is not the only possibility. McMurray et al. (2017) examined pre-lingually deafened CI users in a standard VWP task. They found substantially larger delays (>200 ms). This led to differences in the overall pattern of competition with *reduced* consideration of cohort competitors but increased consideration for rhymes (as in McQueen and Huettig, 2012). The fact that cohorts receive less consideration suggests that the delay in target fixations does not derive from increased competition. Instead, listeners appear to delay lexical processing; then when lexical access begins, they may have already heard information that rules out cohorts—a profile we termed “wait and see”. A similar pattern was also observed in NH listeners hearing severely degraded speech (4-channel vocoding), and

Hendrickson et al. (2020) showed it for NH listeners hearing quiet speech. Thus, this is a general change and not unique to prelingually deaf listeners. To be clear, the term “wait and see” is meant solely as a description of the empirical phenomenon and is not meant to imply any specific mechanism – a point we return to in the general discussion.

To summarize, when listening is somewhat challenging, CI users show moderate slowing and sustain competitor activation (Farris-Trimble et al., 2014). This is at least in part a lexical phenomenon (McMurray et al., 2016) and may be adaptive (McMurray et al., 2019). However, when listening is more difficult, they “wait-and-see”, with much larger delays in lexical access and, as a result show reduced competition from cohorts and increased competition for rhymes (McMurray et al., 2017; Hendrickson et al., 2020).

Sentence Context

Most of the above studies used words in isolation. However, the dynamics of competition may differ when words are heard in sentences (as they typically are). The obvious factor introduced in sentences is syntactic and semantic expectations (which could constrain lexical selection). There is evidence that listeners will use as much information as they have available to anticipate upcoming information in discourse (Altmann & Mirković, 2009; Kamide et al., 2003). While listeners could use these anticipatory mechanisms to help cope with delays in processing brought on by difficult listening scenarios, we are interested in the basic effect of embedding single words in continuous speech (without yet involving reliable anticipatory cues to the target word). Even a simple carrier phrase that is completely non-informative with respect to the target word could have at least four impacts on lexical competition.

First, a delay in lexical access of 70 milliseconds—the delay shown by post-lingually

deaf adult CI users—may seem small. However, if such a delay occurred for each word in even a short phrase, it could compound, and listeners may fall far behind by the end.

Second, even semantically neutral sentences impose cognitive demands. Listeners must construct syntactic and semantic interpretations which could use resources that may be needed for lexical access (Zhang & Samuel, 2018). For example, syntactic complexity may require working memory (Just & Carpenter, 1992), or domain-general cognitive control, especially when misinterpretations are likely to occur (Novick et al., 2005, 2014). Critically, Zhang & Samuel's (2018) study of lexical access suggests that any effect of resource reduction should not be seen in the speed of initial lexical access, but rather later, in the resolution of lexical competition.

Third, prosodic cues could allow the auditory system to predict when a word is likely to begin, making it easier to initiate lexical access (Dilley & Pitt, 2010). This more predictable timing could speed lexical access as opposed to the delays predicted above.

Finally, processing speech in sentences requires a listener to segment the incoming speech signal. This makes competing predictions. One prediction would be that segmentation could require resources that are needed for lexical competition, impeding word recognition. Alternatively, in continuous mapping models (McClelland & Elman, 1986), segmentation is not distinct from lexical access. Rather segmentation occurs because listeners always activate many partial matches to the input (including items with different segmentation such as *car#go* and *cargo*), and competition sorts it out. Thus, the need to segment may lead listeners to adopt faster and more incremental lexical access (which facilitates this segmentation by access approach).

These factors could either facilitate or impede word recognition in sentence context. Thus, the first step is to identify the global effects of a word simply being in a surrounding sentence or phrase. We thus examined word recognition in carrier phrases without constraining

semantic context. Critically, while these phrases were uninformative, the location of the word in the sentence was unpredictable so listeners had to actually process the phrase to identify which word was the target. We asked whether the delays shown by CI users in carriers are similar to those of words in isolation, and if lexical processes change in continuous speech. If CI users show greater delays in sentence contexts (relative to NH), or if they show dramatically impaired accuracy this would suggest the cognitive demands of sentence processing can impact word recognition. Alternatively, CI users could show more immediate processing; this would suggest the demands of sentence processing encourage speeded activation and competition (over and above any cost imposed by the need for more cognitive resources).

While our goals are basic-science, the impact of carrier phrases on word recognition is important clinically because of ongoing debates about the use isolated words or sentences to as a measure of outcomes in hearing remediation (Geller et al., submitted; Mueller, 2001; Taylor, 2003). Understanding how word recognition differs in the context of a carrier could help understand how these tasks relate. This cannot be done simply by comparing existing sentence and word recognition tasks as words, talkers and other factors may differ between tasks. Thus, investigating the effect of simple carrier phrases on lexical processing is a starting point to examine the overall differences between sentences (more broadly) and words in isolation.

The Present Study

The present study uses the VWP to ask how lexical competition changes in continuous speech (relative to isolated words) in both CI users and NH listeners. Target words were acoustically identical across conditions to isolate the impact of the carrier phrases. Phrases were semantically unrelated to the critical word in order to eliminate the effect of semantic/syntactic

expectations to see potential effects of compounding delays, general resource utilization and segmentation from. To ensure that listeners could not just ignore the carrier phrases, we used a large number of frames, both short (*now choose the X*) and long (*in this display, find the picture of the X*), and target words could appear at several positions (*now find the X in this display*). Of course, syntactic and prosodic information offer clues to the position of the target word, but these cannot be useful unless the listener actually processes the phrase. We assessed lexical competition similarly to Farris-Trimble et al. (2014) in a VWP task with pictures corresponding to the target, cohort, rhyme, and unrelated words.

In developing hypotheses, we considered two aspects of lexical competition: the initial activation (of targets and cohorts) and later resolution of competition. If the small delay in individual words compounds across multiple words, we would expect to see delays in initial activation in continuous speech, and a potential decrease in accuracy. Alternatively, if the demands of processing words in continuous speech encourage greater incremental processing (e.g., for segmentation), we would predict faster initial activation.

Effects on later competitor resolution may come from other sources. CI users may show differences from NH listeners in asymptotic target and competitor looks, for example showing reduced target and increased competitor fixations in carrier phrases. This pattern is consistent with two explanations. First, this profile may be more useful in continuous speech: listeners may need to revise after a misrecognition, so they do not fully commit to the target in case they need to reactivate a competitor. Second, this pattern also fits with Zhang and Samuel's (2018) finding that cognitive load impacts late competition resolution and would reflect the increased cognitive demands of sentence processing. The present study cannot disentangle these two explanations.

Finally, a null result is also possible – if carrier phrases exert no effect on recognition,

this might imply that the time course of recognition is entirely driven by the signal quality of the target word itself (which is acoustically identical in both contexts).

There was a choice about how to handle the words in isolation. If the word was heard immediately at trial onset, pre-target fixations would generally be at screen center at that moment. However, in the carrier phrase condition, the delay before the target word (~1 second) would give time for fixations to be directed to the objects, creating differences at baseline. This could be fixed by delaying the presentation of the target word, eliminating the differences at baseline. However, this makes the onset of the word (in isolation) unpredictable, and this contrasts with the more predictable carrier phrase. We dealt with this issue in two ways. First, the primary experiment reported here adopts the latter, delayed onset, approach as we felt the baselining issues created significant statistical issues. However, we also conducted a replication with the immediate onset word in isolation; this shows nearly identical results and is reported completely in Supplement S1 and summarized after the experiment. Second, to deal with the baseline issues in the replication, we use a procedure described in the methods. This was also used in the supplemental experiment for continuity and to eliminate any further between subject-variance in these pre-target fixations.

Finally note that our study used a convenience sample of CI users with a wide array of device types and profiles (though all experienced post-lingually deaf adults). We did not have the sample size for a detailed individual analysis. Thus, we focus on CI users as a group of listeners with long term experience with difficult speech, a point we return to in the discussion.

Materials and Methods

Participants

Twenty-one (10 women) experienced CI patients (greater than 1-year device use) were tested. Participants were recruited from a patient registry maintained by the University of Iowa Dept. of Otolaryngology and tested when they came for their annual device tuning. Participants were required to be between 18 and 75 years, have no known neurological disorders, not have single-sided deafness, and have post-lingual hearing loss. CI users had a mean age of 59.9 years ($SD = 7.8$). Four were unilateral CI users, three were bilateral CI users, three were bimodal CI users, and the remaining eleven used a hybrid CI with aided acoustic hearing on the ipsilateral ear (some also wore a contralateral hearing aid). See Supplement S2 for more detail.

Twenty-one NH controls (10 women) were age-matched to the CI users and recruited through community advertisement. The NH controls had a mean age of 59.6 years ($SD = 9.5$). All NH controls underwent a hearing screening to ensure that their thresholds were no higher than 25 dB in the ranges of 250-4000 Hz. NH control participants were paid \$30.

All participants provided informed consent in accordance with university Institutional Review Board approved protocols for this study.

Design

This experiment used 20 item sets (see Supplement S3) of four words. Each item set consisted of a base word (target, e.g., *mustard*), a cohort (e.g., *mustache*), a rhyme (e.g., *custard*), and an unrelated word (e.g., *penguin*). This resulted in a total of 80 words. In half of the item sets all four words had one syllable, and in the other half they had two. Pictures of each of the four words in a set always occurred together during a trial. Each word in a set was the stimulus on different trials. This created four trial types. When the base word (*mustard*) was the target, each word played their assigned role (e.g., *mustache* was the cohort, *custard* was the rhyme) to create

a target/cohort/rhyme/unrelated trial (TCRU). When *mustache* was the stimulus, there was a cohort (*mustard*), but *custard* and *penguin* are unrelated, a target/cohort/unrelated trial (TCUU). When *custard* was the stimulus, there was a rhyme (*mustard*), but the other words (*mustache*, *penguin*), were unrelated, a target/rhyme/unrelated trial (TRUU). Finally, when *penguin* was the stimulus, all other items were unrelated (TUUU).

The primary experimental condition was *context*: whether words were heard in isolation or in a carrier phrase, manipulated within-subject. In the carrier phrase condition, words were embedded in 40 carrier phrases (Supplement S3). The phrases crossed two factors. First, phrases were evenly divided between short (3-6 words) and long phrases (8-11 words). Second, half of the phrases ended with the target word and half had a post-phrase after the target. These factors were not intended for analysis and were only intended to prevent participants from ignoring the phrase. For each participant, phrases were randomly assigned to target words such that each phrase occurred twice within each set of 80 words.

This context condition was consistent within a block of 80 trials. Blocks alternated between words in isolation or in carrier phrases across a total of 6 blocks, and the initial block type was counterbalanced across subjects. Within a block, we did not restrict target words or phrase (the same context or word could repeat). This was done to prevent participants from discerning the correct response on the basis of which item had not yet been used in that block.

In the carrier phrase condition, listeners were expected to launch several fixations during the phrase, but prior to word onset; thus, the baseline level of fixations would be non-zero. To equate this for the words-in-isolation condition the word was delayed by the duration of a randomly selected carrier phrase (see Supplement S1 for a replication with no delay).

Each word within a set was used as an auditory stimulus 3 times in each context

condition (isolation vs. carrier phrases). The experiment thus had $20 \text{ sets} \times 4 \text{ words/set} \times 2 \text{ contexts} \times 3 \text{ repetitions}$ for a total of 480 trials across 6 blocks.

Stimuli

Auditory stimuli were recorded by a male speaker with a Midwestern dialect. Words and phrases 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. Carrier phrases were recorded with the nonword *tud* as the target². Five recordings of each carrier phrase were made, and the clearest was selected and the *tud* was excised. Fifty ms of silence were added to the beginning of each phrase. A small amount of silence was added to the end of each phrase to ensure a more natural prosody. Phrases had an average length of 1580 ms ($SD=543$).

The target words were recorded in the carrier phrase “choose the picture of the *x*”. Words in isolation were identical to the words spliced into the carrier phrases with the exception that 50 ms of silence was added to the onset of the words in isolation. There were 160 target stimuli (80 words, 2 exemplars per word). Words had a mean duration of 437 ms (range: 262-732).

Every carrier phrase was combined with every target exemplar to create 6400 possible stimuli ($40 \text{ contexts} \times 80 \text{ words} \times 2 \text{ exemplars}$), of which any participant heard 240.

Visual stimuli were clip art images created using a lab procedure designed to ensure that each image is a prototypical depiction of the word (McMurray et al., 2010). Most were drawn from a lab database consisting of images previously developed with this procedure. For each

² *Tud* was used because 1) it is a coronal consonant and a central vowel and was expected to exert less coarticulation on the sentence context than other choices; and 2) because the stop consonant provided closure between the sentence and the target word that offered a clear point for cutting.

image, first, multiple candidates were downloaded from a commercial clipart database. Next, a focus group of lab members reviewed the images and choose the most canonical image and determine what, if any, editing is needed. Next, images were edited to ensure a prototypical color, orientation and size, and to remove any distracting background elements. Final images were approved by a senior lab member with experience with the VWP.

Procedure

The experiment was implemented in Experiment Builder (SR Research Ltd., Ontario, Canada). Testing was carried out in a sound-attenuated booth. Participants were seated in front of a 17" LCD monitor at 1280×1024 pixels. Auditory stimuli were presented in a sound field via JBL Professional 3 Series amplified speakers at $\pm 26^\circ$ from center. Listeners were permitted to set the volume of presentation to a volume comfortable for them.

On each trial, four images (300×300 pixels each) were displayed on the screen at each corner, 50 pixels from the screen edge. Participants saw a red fixation circle intended to draw their gaze back to center after each response. After 500ms the circle turned blue, and participants clicked on it to hear the stimulus. In the carrier phrase condition, this began immediately; in the words-in-isolation condition there was a delay corresponding to one of the randomly selected carrier phrases. Participants were not explicitly told that there would be delays in the word in isolation condition. After hearing the stimulus, participants clicked on the corresponding picture.

Eye-tracking recording and processing

Fixations were monitored with an Eyelink 1000 desktop-mounted eye tracker. A chin rest was used to stabilize the participant's head. The eye-tracker was calibrated using the standard

nine-point procedure. A drift-correct was performed every 20 trials to correct for drifts in the eye-track over the experiment. In the event of a failed drift correction the eye tracker was recalibrated. The Eyelink 1000 uses the location of the pupil and corneal reflection to determine point of gaze every 4 milliseconds. The eye-movement record was automatically parsed into blinks, saccades, and fixations. As with previous studies (McMurray et al., 2010), each saccade was combined with the following fixation to form a “look” which lasted from the initiation of the saccade to the end of the following fixation. When identifying the object associated with each look, image boundaries were extended by 100 pixels to allow for error in the eye track. This extension did not create overlap between any regions of interest.

For analysis, we computed the proportion of trials on which the participant was fixating the target, cohort, rhyme (etc) at each 4 msec window (e.g., Figure 1). Curves were computed separately for each listener and for each condition. Analysis of the fixations used only correct trials, as this allows us to assess identify the timecourse of competition when we know that the participant eventually settled on the correct target. In contrast, including all trials could be problematic as the CI users are more likely to occasionally misperceive the word. On these trials, they would be more likely to fixate the competitors (since they would be clicking on that word), creating an artifact in the averaged time-course of fixations. Fixations for each analysis were drawn from all relevant trial types; Target fixations were estimated from all trials, Cohort from TCRU and TCUU trials, and rhyme from TCRU and TRUU trials. This meant that competitor effects were effectively counterbalanced against any differences in the properties of the two words in the set (e.g., the cohort effect averaged looks to both *mustard* [when *mustache* was the target] and *mustache* [when *mustard* was the target]).

We were concerned that differences in pre-target looking could vary among participants,

creating noise due to basic oculomotor strategies (not word recognition). This was anticipated to be more of a problem in our replication experiment in which the target words were presented without a delay. To eliminate these differences, we subtracted the proportion of looks to the unrelated item at each time point from the looks to the item of interest. This is analogous to baselining the data although it is done at each time (e.g., target at time 200 msec minus unrelated at time 200) and is not relative to a specific pre-stimulus window (as would be done in EEG, for example). Raw (not baseline corrected) data are shown in Supplement S4.

Fixation curves were analyzed using a curvefitting approach based on prior work (Farris-Trimble & McMurray, 2013; McMurray et al., 2019) in which nonlinear functions are fit to each participants' data, and parameters like the slope and asymptote are used as dependent variables.

Target fixations were modeled with a logistic function which predicted the proportion of fixations to the target as a function of time (in milliseconds) after the onset of the target word. We used a 4-parameter logistic function that captured the minimum asymptote (baseline), maximum asymptote (maximum looks), the slope at the transition (rate of change at the crossover point) and the crossover (timing measure). This logistic function was fit using a constrained gradient descent algorithm that minimizes the least squared error while keeping the function between 0 and 1 and constraining parameters in reasonable ways (e.g., the baseline parameter must always fall below the maximum parameter) (McMurray, 2017).

Cohort curves did not conform to the expected shape for all individual subjects (even as the group means did). To overcome this, we jackknifed³ cohort fixation data before curve fitting

³ To jackknife the data, we computed average fixation curves within each carrier condition and listener group as a function of time across all participants, but with one excluded. We next fit curves to this jackknifed data. This procedure is repeated, excluding a different participant each time, resulting in a data set with the same number of subjects as the original data set. These estimates are then compared using test statistics that are adjusted for the fact that there is less variance between "subjects" after jackknifing.

(Apfelbaum et al., 2011; Ulrich & Miller, 2001), and adjusted the F statistic by dividing it by $(n-1)^2$ where n is the number of observations in each cell of the design (F_{jk}). Jackknifing was done separately for each group (NH/CI). Jackknifed competitor fixations were then modeled with an asymmetrical Gaussian function made up of two Gaussians that meet at the midpoint. This allows for separate parameter estimates for the asymptote and slope on either side of the peak of the curve as well as the peak height, and peak timing.

In mapping these parameters to theoretical constructs, we note that changes in the initial activation of targets and competitors should appear in a number of places. When activation is more rapid, we would expect steeper target slopes and earlier crossovers. These will be coupled with higher cohort peaks (since people make more rapid commitments to the cohorts). Conversely late stage competition resolution should appear as differences in the asymptotes of the targets and cohorts, and in the offset slope of the cohort.

Results

Accuracy

First, we examined mouse-clicks with a 2×2 ANOVA (listener group $\times$ carrier phrase) to ensure that listeners were accurate enough in the task to justify the fixation analysis. Both listener groups were generally accurate, though CI users were significantly less so ($M = 93.10\%$ correct, $SD = 5.86\%$) than NH listeners ($M = 99.77\%$ correct, $SD = 0.55\%$; $F(1,40) = 27.58$, $p < .001$). Accuracy was also similar between words in isolation and in carrier phrases, though there were significantly more errors in the carrier phrase condition ($M = 96.00\%$, $SD = 3.63\%$; $F(1,40) = 14.24$, $p < .001$) than in the word in isolation condition ($M = 96.87\%$, $SD = 2.77\%$). There was a significant interaction, $F(1,40) = 7.95$, $p = .007$. This was driven by the fact that the effect of

context was only significant for CI users, $t(20) = 3.58$, $p = .002$, but not for NH listeners, $t(20) = 1.22$, $p = .236$. This suggests that carrier phrases had a detrimental (not facilitatory) effect on CI users' performance. However, even with these differences, accuracy was sufficiently high across both listener groups and conditions to justify analysis of the fixations, and the differences were numerically small and unlikely to substantially bias the fixation analysis.

Figure 1. Looks to the target and competitors after subtracting looks to the unrelated at each time point for both CI users and NH listeners.

Fixations

Figure 1 shows the fixations to the target, cohort and rhyme (after baseline correction) as a function of time. Both groups initiated looks to the target faster when words occurred in carrier phrases. In addition, both groups fixated cohorts earlier and to a slightly higher degree in carrier phrases. CI users still show the previously observed delays relative to NH listeners (Farris-

Trimble et al., 2014), but the effect of carrier phrases was similar to that of the NH.

Target fixations. Figure 2 shows the timecourse of target fixations. Logistic fits were good in all conditions, average $R = .998$ across the four cells of the design (CI/NH [listener group] $\times$ Word in Isolation / Carrier Phrase [context]). There were small differences among conditions (Supplement S5), but fits were highly accurate, and all groups were near ceiling. No subjects were excluded for poor fits.

Figure 2. A) Target fixations as a function of time after subtracting looks to the unrelated item for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters; error bars indicate SEM. B) the crossover; C) the slope; D) peak looks (at asymptote).

The *baseline* parameter showed no significant effect of listener group or context, all $p > .25$. There was a significant interaction, $F(1,40) = 4.44$, $p = .041$. However, paired t-tests revealed no significant difference between carrier phrases and words-in-isolation for either CI

users, $t(20) = 1.67, p = .113$, or NH listeners, $t(20) = 1.29, p = .211$.

Analysis of the **crossover** (Figure 2B) revealed a significant effect of listener group, $F(1,40) = 32.67, p < .001$, as CI users had significantly later crossovers than NH listeners (by 127 ms). There was a marginally significant effect of context, $F(1,40) = 3.91, p = .055$, as both groups showed earlier crossovers when the target was presented in a carrier phrase compared to when the target was presented in isolation (by about 11 ms). There was also a significant interaction, $F(1,40) = 6.46, p = .010$. Follow-up paired t -tests reveal that NH listeners showed earlier crossover points in carrier phrases compared to words-in-isolation, $t(20) = 3.60, p = .002$, while CI users did not, $t(20) = 0.36, p = .722$.

The target **slope** (Figure 2C) patterned differently than the crossover. We found a significant effect of listener group, $F(1,40) = 5.59, p = .023$. NH listeners showed steeper slopes than CI users. There was also a main effect of context, $F(1,40) = 8.54, p = .006$, with no significant interaction, $F(1,40) = 2.93, p = .095$. Both groups showed steeper slopes when words were in isolation compared to occurring in carrier phrases.

Maximum looks to the target (Figure 2D) were scaled with the empirical logit prior to analysis to attain a more Gaussian distribution. This showed no significant effect of listener group, $F(1,40) = 0.50, p = .485$. However, there was a significant effect of context, $F(1,40) = 6.93, p = .012$, and there was a significant listener group $\times$ context interaction, $F(1,40) = 8.16, p = .007$. We followed up on this with paired t -tests for each group (CI and NH). These tests revealed that CI users showed higher maximum target looks for words-in-isolation than in carrier phrases, $t(20) = 4.84, p < .001$. In contrast, NH listeners showed no significant difference between contexts, $t(20) = 0.14, p = .893$.

Cohort Fixations. Cohort fixations in each condition are shown in Figure 3. The fits of

the jackknifed data were good across conditions and for both CI users and NH listeners, mean $R = .989$, with no significant differences (Supplement S5). No subjects were excluded for poor fits.

Onset baseline showed no significant differences between listener group or context and there was no significant interaction, all $p > .65$. As with the target, this suggests that subtracting unrelated items was a useful baseline method. The **onset slope** similarly showed no significant effects of group or context and no significant interaction between the two, all $p > .35$.

Figure 3. A) Cohort fixations as a function of time after subtracting looks to the unrelated, for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters. B) Peak height; C) peak timing; D) offset baseline; E) and offset slope. Note that in B-E, no error bars are included because data were jackknifed prior to curvefitting and there is no clear way to estimate standard error for jackknifed data.

Peak height (Figure 3B) showed significant differences between listener groups, with CI users showing reduced peak cohort fixations compared to NH, $F_{jk}(1,40) = 9.99$, $p = .003$. There was a significant effect of context with increased peak looks in carrier phrases compared to

words-in-isolation, $F_{jk}(1,40) = 12.32, p = .001$. There was no significant interaction between listener group and context, $F_{jk}(1,40) = 0.16, p = .686$. **Peak timing** (Figure 3C) did not differ significantly by group or context, and there was no significant interaction, all $p > .4$.

Offset baseline (Figure 3D) showed a marginally significant effect of group, $F_{jk}(1,40) = 3.33, p = .076$. CI users showed slightly higher baselines at the end of the trial ($M=.006$), relative to NH ($M=.002$). There was no significant effect of context, $F_{jk}(1,40) = 2.72, p = .107$, and no significant interaction, $F_{jk}(1,40) = 0.54, p = .465$. **Offset slope** (Figure 3E), however, showed a significant effect of listener group with CI users taking more time to suppress cohorts than NH listeners, $F_{jk} = 7.52, p = .009$. There was no effect of context, $F_{jk}(1,40) = 0.58, p = .450$, and no interaction, $F_{jk}(1,40) = 0.32, p = .570$.

Figure 4. Looks to the rhyme after subtracting looks to the unrelated item at each time point for both listener groups and sentence conditions.

Rhyme Fixations. Figure 4 shows rhyme fixations in each condition over time. Even the group-level looking showed non-canonical patterns, particularly in CI users. This was driven by the fact that many individual CI users fixated the rhymes more than the unrelated baseline even before word onset. Because of these early looks, rhyme looks could not be fit with the asymmetrical Gaussian. This difference in baseline looking (unique to CI users) may suggest a meta-linguistic strategy on these trials (as rhyme trial data can only be taken from TCRU and TRUU trials). Rhymes in TRUU trials may simply be more salient and CI users may take advantage of this to cope with difficulty processing the input.

When modeling the CI data, a variety of curve-fitting procedures were exhausted without success. Supplement S6 presents several coarser analyses of rhyme fixations across listener group and context. In these analyses, rhymes are active later for CI users than for NH listeners, stay active for a greater extent of the trial, and reach marginally higher peak fixations. We are hesitant to draw strong of conclusions regarding rhymes, however, given the relatively weak effects and the unexplained difference at baseline.

Figure 5. A) Target fixations as a function of time after subtracting looks to the unrelated item for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters; error bars indicate SEM. B) the crossover; C) the slope; D) peak looks (at asymptote).

Replication Summary

As we described, one concern with this experiment was that in the words-in-isolation condition onset of the target word was unpredictable, whereas if listeners were following the carrier phrase the onset was predictable in this condition. While this was necessary to achieve a comparable baseline, some of the differences between the two context conditions could be due to predictability. We thus replicated this experiment using identical methods, except that the words presented in isolation did were always presented 50 msec after clicking on the fixation circle. Twenty-two CI users with a similar profile to the primary experiment were tested.

Figure 6. A) Cohort fixations as a function of time after subtracting looks to the unrelated, for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters. B) Peak height; C) peak timing; D) offset baseline; E) and offset slope. Note that in B-E, no error bars are included because data were jackknifed prior to curvefitting and there is no clear way to estimate standard error for jackknifed data.

A full report is available in Supplement S1 (Figure 5, 6 for targets and cohorts). The results are strikingly similar across the two experiments. In this experiment, CI users showed a delay in target fixations relative to NH, a reduction in peak cohort fixations, and a reduced asymptote for the target. The effect of context was also consistent across experiments with a faster commitment to the target in both groups in carrier phrases. The effects on maximum target looks differed between experiments, but the replication was consistent with the broader finding of a larger effect of sentence context on the asymptote in CI users.

General Discussion

The primary goal of this study was to understand the impact of non-informative carrier phrases on the dynamics of word recognition. This was motivated by specific issues raised by CI users, but as the role uninformative carrier phrases on the dynamics of word recognition has not been widely studied in the basic science of language processing this study adds to our understanding of these impacts as well. We start by addressing the overall difference between CI and NH listeners. We then turn to the influence of carrier phrases on both the earliest moments of processing, and the later resolution of competition.

CI vs. NH listeners

Across two experiments, CI users showed somewhat larger delays ($M = 135$ ms) (in both context conditions) than have been previously observed (prior delays are typically around 75 ms: Farris-Trimble et al., 2014). CI users also showed decreased peak cohort fixations, whereas Farris-Trimble et al. (2014) found increased peak cohort fixations for similar CI users. CI users show greater rhyme consideration than NH listeners (Supplement S6). These three findings look a lot like the “wait-and-see” pattern described earlier for prelingually deaf children (McMurray et al., 2017), and for NH listeners hearing substantially degraded input or soft speech (Hendrickson et al., 2020; McMurray et al., 2017). This is surprising given that the population was post-lingually deaf and is a fairly close match to that of Farris-Trimble et al. (2014).

One of our hypotheses was that the delay observed previously in isolated words might compound across a sentence to create even larger delays. However, even in this population where we expected the delay in isolated words to be small, we found a pattern of lexical competition changes normally associated with listeners who encounter much greater difficulty. It could be that we happened to test a sample of CI users who are simply experiencing greater

difficulty than would be expected with their CI. However, as Supplement S2 indicates, CI users were experienced, and nearly all showed good speech perception outcomes. Moreover, this was observed in a sample of 43 CI users across both experiments. Unfortunately, our sample sizes in each experiment were not sufficient to attempt a serious individual differences analyses (e.g., as a function of device type or performance), but this is an important area for future work.

There are two possibilities for these differences. First, Farris-Trimble et al. (2014) may have sample unrepresentatively good performers. If so, our data suggest that far more CI users exhibit this profile than previously observed. Perhaps this profile is much more common, and perhaps helpful, even for CI users with relatively good outcomes. Alternatively, the structure of the experiments in this study may have led CI users to adopt the “wait-and-see” profile even if they would not normally exhibit this in a typical experiment with only words in isolation. Specifically, listeners could be adapting to the fact that on many trials a sentence may be present (even if that adaptation is not helpful on all trials). That is, listeners may flexibly adapt lexical processing to task-demands across the experiment, even if they cannot do so at a finer timescale (between 10-minute blocks). It is not clear whether this adaptation is helpful.

Critically, it is important to note that wait-and-see is meant only as a description of the empirical pattern of data. The underlying mechanisms are unclear. They could derive from a delay in lexical access, reduced signal fidelity or both (c.f., McMurray, Apfelbaum and Tomblin, submitted). Understanding which of these mechanisms is at play is critical for understanding how CI users achieve this adaptation and is an important area for future work.

Surprisingly, CI users not only showed a “wait-and-see” profile here, but also showed evidence of sustained competitor activation. CI users took longer to suppress the competitor than NH. Moreover, they show a reduced asymptote to the target, and the analyses across both

experiments (Supplement S1) suggest they suppress the competitor less fully than NH listeners. This suggests that these two profiles are not mutually exclusive—CI users can both wait and see and withhold a complete commitment to the target word. These profiles may derive from different causes and solve different problems. This combination of “wait-and-see” and sustained competitor activation may be ideal when CI users process sentences.

Effect of Continuous Speech: Timing and Activation Rate

Overall effects of carrier phrases on the *timing* of target fixations were small. NH listeners showed earlier crossover points in our main experiment when listening to words in continuous speech. However, the benefit was relatively small, and it was not found in our supplemental follow-up. In contrast, both groups showed a steeper slope in words in isolation than in carrier phrases. Normally crossovers are anti-correlated with slope: when listeners show a delayed crossover, it is because they have a shallower slope (Farris-Trimble & McMurray, 2013; McMurray et al., 2010, 2019). Here we see the reverse in our primary experiment (a later crossover, but steeper slope in words-in-isolation) or no correlation in the replication (no change in crossover, but a steeper slope in words-in-isolation).

Given this, steeper slopes suggest that when words occur in isolation it takes longer to initiate lexical access even if processing “ramps up” to make up for this delay. In contrast, in carrier phrases, target fixations numerically begin earlier (though this is not directly captured in any of our parameters) and show similar crossover times, even as they start earlier. Notably, competitor activation was also significantly altered by the presence of carrier phrases in both groups. Even for CI users, who showed lower overall cohort activation than NH listeners, embedding acoustically identical target words into a carrier phrase led to higher peak cohort

fixations. Thus, this too appears to be general difference due to context.

One explanation for this pattern of results would be the need for immediate processing. Carrier phrases increase the need for immediate and incremental processing because auditory input precedes and often follows the target word. Listeners do not have the luxury of time, and this could lead them to adopt this more immediate processing mode. Critically, more immediate processing also leads to information early in the word being weighted more heavily. Consequently, target fixations may get above baseline faster, and they may also show increased cohort fixations, since the earliest bits of information are consistent with both. This is exactly what was observed across both experiments and is consistent with what we have termed increased *activation rate* (McMurray et al., submitted).

It may be the need for segmentation that drives listeners to more heavily weight early information during processing. Continuous mapping models (such as TRACE: McClelland & Elman, 1986) rely on competition to handle word segmentation. These models activate a range of possible segmentations and let competition arrive at the optimal parse for the input. This allows these models to accomplish segmentation without any dedicated segmentation processes. If segmentation is accomplished via competition and listeners need to process speech in phrases, heavily weighting early information would allow the competition to begin earlier; the need for this may be enhanced in uninformative carrier phrases where semantic context is not available to guide segmentation. This could lead to overall increases in the speed of both lexical access and segmentation as word boundaries may be discovered more quickly.

Even as listeners initiated lexical access faster in continuous speech, it remains that overall slope was shallower in this condition. This suggests a slower activation rate by the end of the trial. Listeners may be attempting to utilize semantic and syntactic information from the

carrier phrase to constrain lexical access and rule out competitors. However, as the phrases in this study were non-informative, this may impose processing costs that slow lexical processing after initial access. In normal discourse, such a process would likely speed activation by ruling out competitors inconsistent with the semantic context (Dahan & Tanenhaus, 2004), but in this study this process is likely costly as it offers little to no constraint on lexical access. This again speaks to the flexibility of lexical access dynamics.

It is important to note that this effect was much stronger in the primary experiment than in the replication. In the primary experiment it appeared as a significant effect on slope, but only a marginal main effect on crossover (which was larger in NH listeners). In contrast, in the replication study it only appeared in the slope. The larger effect in NH in the primary experiment may derive from the fact that this effect would likely be harder to observe in CI users because of their substantial delays in processing. The differences between experiments may derive from the predictability in word onsets. Carrier phrases provide timing cues as to when each word is about to begin which could help listeners prepare to initiate lexical access or to launch an eye-movement (Dilley & Pitt, 2010). In the word-in-isolation condition of the main experiment, the seemingly random delays introduced meant that only the sentence context condition had a predictable target-onset. As a result, the crossover difference observed in NH listeners could be due to either preparation (in carrier phrases) or surprisal (in the word-in-isolation condition). However, in the replication, the word was predictable in both cases, which may explain why the effect was weaker. However, the significant effect on slope – even in the replication – suggests this cannot entirely explain the effect.

However, at the broadest level, CI users appear to show qualitatively similar effects of carrier phrases on lexical processing to NH listeners, even as CI users still experience delays in

fixating the target. The impact of carrier phrase on crossover was minimal for both groups of listeners; both groups seem to weight early information more heavily for words in phrases than words in isolation; and both groups show overall shallower target slopes in sentence contexts. This is not consistent with our hypothesis that continuous speech could lead to catastrophic delays in processing for CI users. Perhaps this is unsurprising given CI users' general success at everyday communication. The phrases in this study, however, were intentionally non-informative so it is encouraging that even in the least helpful contexts, sentence processing does not impose significant costs in word recognition for CI users. Rather, the effect of carrier phrases suggests that CI users can harness similar segmentation strategies to those that NH listeners use.

Competition Resolution in Continuous Speech

Across both experiments some results suggest CI users did not resolve competition as fully as NH listeners. Our primary experiment found competitor fixations took significantly longer to reach baseline in CI users (though this was not significant in the replication); in both experiments, the offset baseline for the cohort approached significance, and a combined analyses (Supplement S1) showed robust evidence for this. We also found indirect evidence for this in target fixations, where the maximum looks in carrier phrases were reduced in CI users relative to NH listeners (in both experiments). This—in addition to the increases in cohort fixations—is a strong indicator (and perhaps statistically more reliable) marker that CI users are not fully committing the to the target—the sustained activation profile. This suggests CI users keep competitors active and do not fully commit to the target even at the end of processing. This may be adaptive: when mistakes in recognition are more common it would make sense to hold onto competitors, even if only to a small degree, as it would make it easier to reactivate these items to

correct for potential misrecognitions (McMurray et al., 2009). We note that the phrase that follows the target word (in half the carrier phrases) was uninformative; thus the decision to do this is likely more of a heuristic applied to any sentence, and not tied to the specific content (and see Sarrett et al., 2020 for converging evidence for the maintenance of phonetic ambiguity).

These findings support a role for cognitive adaptation of lexical processing that may be intended to maximize the potential to recover from misrecognitions. That is, by withholding a complete commitment, CI users may be more flexible in recovering from a misperception. Indeed, the slower growth of target fixations later in the trial (in carrier phrases) may also support this as another marker that listeners avoid making strong commitments too rapidly. Critically, it is in sentence context where this approach would be most useful (since later words may provide information or it may take time to integrate semantic or syntactic expectations). This suggests CI users exhibit this sustained activation strategy specifically in contexts where it would be most beneficial.

Implications

For the purposes of clinical measures, we found that accuracy was lower (particularly for CI users) when words were embedded in continuous speech. Our task is unlike any of the clinically common sentences recognition tasks: it was a 4AFC closed set task, carrier phrases were uninformative, and the response was picture selection, not speech production. Nonetheless, even without these critical aspects of clinical sentence-based tasks, embedding words in carrier phrases led to more errors. It is not clear if these increased errors reflect more challenging perceptual processes, or something about the higher-level demands of sentence processing (e.g., if syntactic parsing is resource demanding). However, two reasons favor the latter. First, the

auditory input was identical across the conditions. Second, the eye-movement results did not show large delays in processing the specific target word between the conditions. This adds to the evidence sentence level tasks invoke more than just auditory/perceptual processes. While such demands may increase their real-world predictability, they may also make them less diagnostic of specific perceptual issues (Geller et al., submitted). However, it is encouraging to note that the lack of compounding delay suggests that CI users may be relatively unaffected by the short sentences used in many clinical assessments. In fact, embedding words in sentences may be ideal for encouraging variance in word recognition tasks if participants are performing near ceiling (making it difficult to detect differences).

Limitations

There are several limitations to this study. First, we used non-informative carrier phrases which are uncommon in everyday language use. This makes it impossible to tell if these effects (like increased competitor competition) would be observed with more natural sentences. However, had we used more natural sentence contexts the semantic constraints alone may have obscured any differences caused simply by embedding words in continuous speech.

Second, the patterns of rhyme fixations in both experiments suggest that CI users may be exhibiting some meta-linguistic strategy. It could be that CI users pick up on the target-rhyme relationship more easily given people's wide awareness of rhymes. They may then exploit this by launching fixations to the rhyme above baseline. Even discounting the early looking, the rhyme effects in both experiments were weak, making it hard to detect effects of listener group or context condition. More careful construction of rhyme sets may eliminate both of these issues in future studies. However, this strategy did not appear to affect the cohort or target fixations

(which were at baseline), so it is unlikely to affect our primary conclusions.

Third, neither the primary experiment nor the replication was able to perfectly match the words-in-isolation to the carrier phrase condition in terms of the predictability of the word. The primary experiment added “carrier phrase duration” quantity of silence to the words in isolation. This equated the time for visually scanning the display between the conditions, but as a result the onset of the words in isolation could not be predicted (as it could in the phrases). The replication controlled for this with a very predictable word onset (always 50 ms after mouse click). However, this allowed more time to scan the scene in the carrier phrase condition. Even as neither is perfect, the fact that the pattern of results was broadly similar across the two experiments seem to make this a small drawback.

Finally, our study compares CI users *as a group* to NH listeners. Our convenience sample of CI users was necessarily broad, with substantial heterogeneity in device type, age, and etiology and length of deafness (Supplement S2). Any of which could influence results. Our sample sizes were insufficient for any serious individual differences analyses (e.g., a correlation or sub-group approach), and though the VWP shows decent test/retest reliability (Farris-Trimble & McMurray, 2013), it is not generally used as a single subject measure. Thus, we focused on group differences, which treats a particularly heterogenous population as one group. There may be important differences among CI users. For example, hybrid and bimodal listeners with access to F0 may be able to better segment words from running speech than electric only listeners (Spitzer et al., 2009). These are important avenues for future work. At the same time, we note that at the level of lexical processing (as studied with the VWP), the pattern of lexical competition shown by CI users often matches that of NH listeners with vocoded speech - a mediocre approximation of real CI input (Farris-Trimble et al., 2014; McMurray et al., 2017),

and also with background noise (Brouwer & Bradlow, 2016), and even in quiet speech (Hendrickson et al., 2020). Thus, at the level we are studying, the specifics of the signal processing may not matter substantially. Instead, we would argue that in the context of this experiment, our CI users should be viewed as a fairly representative sample of individuals with long term post-lingual experience with degraded speech input.

Conclusions

While CI users showed substantial delays in target fixations, they showed no evidence of catastrophic delays when words were presented in non-informative carrier phrases. In both carrier phrases and isolated word conditions, CI users show decreased cohort competitor fixations during processing compared to NH listeners, though they also sustain competitor activation later into the trial as well as well. This suggests that real-time processing is altered in multiple ways depending on the task demands. Moreover, carrier phrases lead listeners (both NH and CI) to weight early information more heavily than when words are presented in isolation as evidenced by increased activation of cohort competitors. Finally, late in the trial, CI users, particularly in carrier phrases, show less complete commitment to the target, and increased competitor activation. These results suggest that the lexical system is flexible and can adapt to fit the needs of the listener.

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SUPPLEMENTAL DIGITAL CONTENT

**Lexical Access Changes Based on Listener Needs:
Real-Time Word Recognition in Continuous Speech in Cochlear Implant Users**

Running Head: LEXICAL ACCESS IN CONTINUOUS SPEECH

Francis X. Smith
And
Bob McMurray

Dept. of Psychological and Brain Sciences and
Dept. of Otolaryngology
University of Iowa

Corresponding Author
Francis X. Smith
Dept. of Psychological and Brain Sciences
255 PBS
University of Iowa
Iowa City, IA 52245
Francis-smith@uiowa.edu
319-335-0692

S1. Replication Study

The primary experiment controlled the timing of the target words by adding an amount of silence identical to the length of a randomly chosen carrier phrase to the onset of each word in isolation. This ensures that in both context conditions, listeners have similar time to scan the scene and leads to similar amounts of baseline looking. However, it also creates a predictability confound: in carrier phrases the target word is fairly predictable (if the listener is actually processing the phrases) while in the word-in-isolation condition it is not. We thus conducted a replication in which the word-in-isolation condition had no delay between the onset of the trial and the stimulus – making the word perfectly predictable in both cases (though creating issues in the baseline fixations).

Materials and Methods

Participants. Twenty-two experienced CI users (with more than 1-year of device use; 11 women) were recruited for this study from the same patient registry as in the primary experiment. Eligibility criteria were the same as in the primary experiment. No participant was allowed to participate in both. Listeners had a mean age of 63.7 years ($SD = 6.2$). Three participants were unilateral CI users, four were bilateral CI users, four were bimodal CI users, and the remaining eleven used a hybrid CI with aided acoustic hearing on the ipsilateral ear (some also wore a contralateral hearing aid). See Supplement S2 for details on the participants.

NH controls were recruited through community advertisement. This resulted in 18 NH controls (13 women). Their average age was slightly lower than that of the CI participants ($M = 54.0$, $SD = 15.3$). All NH controls underwent a hearing screening to ensure that their thresholds were no higher than 25 dB in the ranges of 250-4000 Hz. NH control participants were paid \$30. All participants provided informed consent in accordance with university Institutional Review Board approved protocols for this study.

Design. The design of the replication experiment was similar to the primary experiment with several exceptions. First, we removed the phrase-matched delay in the word-in-isolation condition to enhance the predictability of word onset in this condition. Second, this reduced time spent during each trial in the word-in-isolation condition allowing for more trials within an experimental session. As a result, each auditory stimulus was presented 4 times / context condition (as opposed to the 3 / condition in the main experiment). This resulted in 640 total trials across 8 blocks.

Stimuli. The stimuli were the same as those described in the primary experiment (see Supplement S3 for a complete list).

Procedure. The procedures were the same the primary experiment.

Eye-movement recording and analysis. Eye-movements were recorded, processed and analyzing using a similar technique to the primary experiment. Critically, fixations were baselined by subtracting the unrelated fixations from the target/cohort and rhyme fixations prior to analysis (see Supplement S4 for visualizations of this data prior to baselining).

Results

Accuracy. Both groups were generally accurate in ultimately recognizing the word (selecting the correct picture), though CI users were less accurate ($M = 93.56\%$ correct, $SD = 4.91\%$) than NH listeners ($M = 99.67\%$ correct, $SD = 0.50\%$). Accuracy was also similar between context conditions, though there were more errors in the carrier phrase condition ($M =$

Figure S1.1. Looks to the target and competitors after subtracting looks to the unrelated at each time point for both CI users and NH listeners. The vertical dashed lines represent the 200ms oculomotor delay.

96.33% correct, $SD = 3.17\%$) than with words in isolation ($M = 96.98\%$ correct, $SD = 2.24\%$). Both of these differences were significant in a 2×2 ANOVA on accuracy as a function of listener group and context condition. There was a significant main effect of listener group, $F(1,38) = 29.42$, $p < .001$, and a significant effect of context, $F(1,38) = 5.39$, $p = .026$. There was no interaction, $F(1,38) = 2.49$, $p = .123$.

Fixations. Figure S1.1 shows looks to the various items on the screen as a function of time after target onset after baselining (Supplement S4 for visualizations without baselining). Early on, both groups looked more at the cohort than unrelated items (cohort fixations were above 0), suggesting they exhibited incremental processing. NH listeners showed slightly earlier looks to both the target and cohort than CI users and more cohort fixations. CI users also showed slightly lower overall looks to the target, and competitor fixations remained above baseline longer than NH listeners. Both of these patterns are consistent with Farris-Trimble et al. (2014). Further, both groups look slightly earlier to target words when words are presented in carrier phrases rather than in isolation (as was observed in the primary experiment). To analyze these results, we examined each candidate item type individually (Target, Cohort, Rhyme) on the appropriate trial types using the same process as the main experiment.

Target fixations. Fixations to the target as a function of time, listener group and context condition are shown in Figure S1.2. Logistic fits were good across both groups and both conditions, with an average R of .998 across all four cells of the design. While CI users ($M = .998$) showed a significantly poorer fit than NH listeners ($M = .999$) (see Supplement S5),

Figure S1.2. A) Target fixations as a function of time after subtracting looks to the unrelated item for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters; error bars indicate SEM. B) the crossover (in milliseconds); C) the slope (change in proportion looks per 100ms); D) maximum looks (at asymptote).

differences were numerically negligible. Each of the four parameters for each subject was then compared across condition and group with 2x2 mixed ANOVAs assessing the effect of context (carrier phrase vs. word-in-isolation) and group (CI vs. NH).

The **baseline** parameter showed no significant differences between group or context and no significant interaction, all $p > .20$. This suggests that the subtraction of looks to unrelated items appropriately corrected looks to the target, as it does not cause differences in the baseline before the onset of the target word.

Crossover (Fig. S1.2B) showed a significant effect of listener group, $F(1,38) = 45.89$, $p < .001$, as CI users had significantly later crossovers than NH listeners (by on average 143 ms). There was no significant effect of context, $F(1,38) = 1.22$, $p = .276$, and no significant interaction, $F(1,38) = 2.16$, $p = .150$.

The **slope** of target fixations patterned similarly to the primary experiment (Figure S1.2C). We found a significant main effect of listener group, $F(1,38) = 26.32$, $p < .001$, and context, $F(1,38) = 19.29$, $p < .001$, with no significant interaction, $F(1,38) = 1.09$, $p = .302$. NH listeners showed steeper slopes than CI users, and both groups showed steeper slopes when words were in isolation than in carrier phrases.

For analysis, **maximum looks** to the target (Figure S1.2D) were first scaled with the empirical logit. There was a significant effect of listener group, $F(1,38) = 10.44$, $p = .003$. This was due to the fact that CI users showed reduced maximum looks relative to NH listeners. There

Figure S1.3. A) Cohort fixations as a function of time after subtracting looks to the unrelated, for each listener group and sentence context condition (the dotted vertical line represents the 200ms oculomotor delay). Panels below indicate individual curvefit parameters. B) Peak height; C) peak timing (ms); D) offset baseline; E) and offset slope. Note that in B-E, no error bars are included because data were jackknifed prior to curvefitting and there is no clear way to estimate standard error for jackknifed data.

was also a main effect of context, $F(1,38) = 4.21$, $p = .047$ and a significant interaction, $F(1,38) = 6.27$, $p = .017$. Paired-sample t-tests revealed that there was no difference in maximum looks between contexts for CI users, $t(21) = 0.43$, $p = .669$, while NH listeners showed higher maximum looks when words were embedded in carrier phrases, $t(17) = 2.52$, $p = .022$.

Cohort fixations. The timecourse of cohort fixations as a function of listener group and context is shown in Figure S1.3. As in the primary experiment, Cohort fixations were jackknifed prior to curvefitting, and F statistics were adjusted to account for jackknifing. Fits were good across conditions and for both CI users and NH listeners, mean $R = .989$ with no significant differences (Supplement S5). Each of the six parameters was then examined in a 2×2 ANOVA assessing the effect of context (sentence-context vs. word-in-isolation) and group (CI vs. NH).

Onset baseline showed no significant differences between group or context and there was no significant interaction, all $p > .10$. As with the target baseline, this suggests that subtracting unrelated items serves as a useful baselining method. The **onset slope** parameter similarly showed no significant differences between group or context and no significant interaction between the two, all $p > .20$.

Peak height (Figure S1.3B) showed significant differences between listener groups, with CI users showing reduced peak fixations compared to NH listeners, $F_{jk}(1,38) = 9.11$, $p = .005$. There was also a significant effect of context ($F_{jk}(1,38) = 15.29$, $p < .001$): when the target word

was presented in a carrier phrase, peak looks increased. The listener group $\times$ context interaction was marginally significant, $F_{jk}(1,38) = 3.52$, $p = .068$, driven by the fact that the increase in competitor peak was numerically larger in NH listeners.

Peak timing (Figure S1.3C) similarly showed significant differences between groups, with CI users showing a delayed cohort peak relative to NH listeners (by an average of 90 ms), $F_{jk}(1,38) = 14.29$, $p < .001$. There was no significant effect of context, $F_{jk}(1,38) = 1.03$, $p = .316$. There was no significant group $\times$ context interaction, $F_{jk}(1,38) = 0.16$, $p = .693$.

Offset baseline (Figure S1.3D) showed a marginally significant effect of listener group, $F_{jk}(1,38) = 4.09$, $p = .050$. CI users had numerically higher baselines ($M = .0045$) than NH listeners ($M = .0000003$). There was no effect of context, $F_{jk}(1,38) = 1.50$, $p = .228$, and no interaction, $F_{jk}(1,38) = 1.50$, $p = .228$. The **offset slope** (Figure S1.3E) showed no significant effect of listener group or context and there was also no significant interaction, all $p > .10$.

Rhyme Fixations. As in the primary experiment, CI users fixated the rhyme above baseline even before target word onset (Figure S1.4). Because of this we could not adequately fit curves to the rhyme data for CI users and thus could not rely on the statistical approach we used for cohort fixations. As in the primary experiment, we report coarser analyses of rhyme fixations, to draw tentative conclusions (Supplement S6). They find, as in the main experiment, that rhymes were fixated for a greater extent of the trial by CI users than by NH listeners, and they showed higher peak fixations, though the timing of rhyme activations does not differ by group.

Figure S1.4. Looks to the rhyme after subtracting looks to the unrelated item at each time point for both listener groups and sentence conditions (the dotted vertical line represents the 200ms oculomotor delay).

Discussion

With respect to the effect of listener group, CI users showed delayed lexical activation relative to NH listeners. CI users were about 143 ms slower to fixate the target than NH listeners (target crossover, Figure S1.2B). Peak looks to cohort competitors were also about 90 ms later than NH listeners (Figure S1.3C). These delays were also observed in carrier phrases, extending prior work which focused on words in isolation (Farris-Trimble et al., 2014).

The delays observed in the present study however were larger than previously reported among post-lingually deafened CI users (Farris-Trimble et al., 2014). We also saw a *decrease* in peak cohort looking in CI users (Figure S1.3B) which was not observed earlier. The larger delays in lexical activation combined with the decrease in peak target looks and cohort competitor activation levels suggest that CI users in this experiment were exhibiting something closer to the “wait-and-see” pattern of lexical access, which is not predicted for this population by prior work (Farris-Trimble et al., 2014). CI users also showed a slight increase in cohort competitor activation at offset of the trial which, while only marginally significant, suggests they may have been preserving some competitor activation to correct for misperceptions.

The effects of carrier phrases on the speed of lexical access were quite similar across the listener groups. Both CI users and NH listeners showed no difference in the time of their crossover point between words presented in carrier phrases compared to words presented in isolation. The timing of peak looks to the cohort were similarly unaffected by context. Carrier phrases seem to present no difficulty for committing to the target for either group. However, both groups showed a significant increase in target slope when words were presented in isolation. This suggests that lexical access may initiate slightly earlier in continuous speech than in isolation. Conversely, even as the crossover is reached at similar times in both conditions, in isolation, lexical access may begin slightly later and then “ramp up” faster.

In general, CI users showed a similar response to carrier phrases as NH listeners. However, an interaction was observed in the resolution of competition late in the trial. Maximum target looks (at asymptote) showed a larger difference between CI users and NH listeners in carrier phrases than with words in isolation. These larger differences suggest that CI users may alter how strongly they resolve competition in sentence contexts.

Cross-Experiment Analyses

We originally hypothesized that CI users would show sustained competitor activation, as had been observed in previous research with post-lingually deafened adults (Farris-Trimble et al., 2014). The pattern of results across the two experiments revealed some signs of this profile. In particular, maximum target fixations were reduced in CI users, particularly in carrier phrases. However, cohorts showed mixed results with a significant effect on the offset slope (but not the asymptote) in the primary experiment, and a marginally significant effect on asymptote here.

One explanation may be that each experiment lacked the power to detect the effects of sustained competitor activation due to the jackknifing procedure used for cohorts. This procedure is quite conservative in its corrected F -statistic. Given this pattern, and the fact that the two experiments generally showed a similar pattern of results, we combined data from both to determine if there was evidence for sustained activation in analysis with greater power. We were hesitant to apply this approach to all of the parameter estimates, as the experiments differed in critical aspects of timing that may affect the earliest fixations. However, late measures (such as offset slope and offset baseline of cohorts) would be unlikely to be affected by these timing differences. Moreover, this procedure was not necessary for target looks as they were not

jackknifed. Thus, we performed a combined analysis of the offset slope and offset baseline using a $2 \times 2 \times 2$ mixed ANOVA using listener group, context, and experiment as factors.

Offset slope showed a significant effect of listener group, with CI users taking longer to suppress cohorts than NH listeners, $F_{jk}(1,78) = 9.77, p = .003$. No other main effect was significant, all $p > .3$, and there were no significant interactions. The **offset baseline** similarly showed a significant effect of listener group, as CI users looked to cohorts more at the end of the trial than NH listeners, $F_{jk}(1,78) = 7.31, p = .010$. There was also a significant effect of context, as carrier phrases led to higher looks to cohorts at the end of the trial than words in isolation, $F_{jk}(1,78) = 4.12, p = .049$. Experiment did not have a significant effect and there were no significant interactions, all $p > .2$.

As this analysis was post-hoc, we should treat results with caution, particularly main effect of context on the offset baseline which was not observed in the analyses of each experiment. However, the pattern of results with respect to listener group are consistent with the marginal effects seen in each experiment, and they fit the profile of sustained competitor activation. This suggests that the individual experiments simply lacked the power to detect the effect. CI users do indeed seem to keep competitors active, and this may allow for easier corrections in response to misperceptions.

S2. Participants

Table S2.1. *Description of CI users in the primary experiment.*

Missing values in the Onset of Deafness column indicate a gradual hearing loss. AZ-Bio and CNC word scores are taken from the hearing configuration used by the patient on the day of the experiment.

Configuration	Gender	Age (yrs)	Age at Implantation	Onset of Deafness	Ear	Manufacturer	Implant Model	Etiology	AZBio%	CNC Word%
Bilateral	Male	69	60	44	B	Cochlear	Nucleus CI 512 (CA)	Unknown	92	93
Bilateral	Female	60	55	45	B	AB	Clarion HiRes 90k	Hereditary	97	88
Bilateral	Female	63	52	47	B	Cochlear	L - Nucleus CI 24 RE R – Nucleus CI 512 (CA)	Unknown	79	86
Bimodal	Female	54	48	47	R	Cochlear	Nucleus CI 422	Unknown	92	99
Bimodal	Female	54	51	30	R	AB	Clarion HiRes 90k	Unknown	75	42
Bimodal	Male	44	43	42	R	AB	Clarion HiRes Ultra Slim J	Unknown	62	30
Hybrid	Female	58	52	24	R	Cochlear	Nucleus Hybrid L24	Unknown	84	90
Hybrid	Female	41	36	---	R	Cochlear	Nucleus Hybrid L24	Unknown	82	91
Hybrid	Male	64	59	50	L	Cochlear	Nucleus Hybrid S12	Family History	73	60
Hybrid	Male	58	54	50	L	Cochlear	Nucleus Hybrid L24	Unknown	26	30
Hybrid	Male	62	57	45	L	Cochlear	Nucleus Hybrid L24	Unknown	71	86
Hybrid	Female	61	57	40	R	Cochlear	Nucleus Hybrid L24	Unknown	88	74
Hybrid	Male	55	52	35	R	Cochlear	Nucleus Hybrid L24	Unknown	92	87
Hybrid	Male	70	67	30	R	Cochlear	Nucleus Hybrid L24	Unknown	85	86
Hybrid	Male	71	67	60	R	Cochlear	Nucleus CI 422 + HA	Unknown	51	74
Hybrid	Female	61	60	45	L	Cochlear	Nucleus S12	Family History	92	91
Hybrid	Male	70	68	64	R	Cochlear	Nucleus Hybrid L24	Unknown	38	86
Unilateral	Female	58	29	22	L	Cochlear	Nucleus CI 24M	Hereditary	83	63
Unilateral	Male	60	56	55	L	Cochlear	Nucleus CI 422	Unknown	95	96
Unilateral	Female	62	36	36	L	AB	Clarion Radial Bipolar/Standard 1.0	Otosclerosis	90	79
Unilateral	Male	53	31	27	R	Cochlear	Nucleus CI 24M	Unknown	82	57

Table S2.2. *Description of CI users in the supplemental experiment.*

AZ-Bio and CNC word scores are taken from the hearing configuration used by the patient on the day of the experiment.

Configuration	Gender	Age (yrs)	Age at Implantation	Onset of Deafness	Ear	Manufacturer	Implant Model	Etiology	AZBio%	CNC Word%
Bilateral	Female	42	25	19	B	AB	Clarion HiFocus II-CII	Hereditary	43	78
Bilateral	Female	57	40	31	B	AB	Clarion HiFocus II-CII	Unknown	90	83
Bilateral	Female	59	50	25	B	Cochlear	L – Nucleus CI 512 R – Nucleus CI 24 RE	Unknown	92	92
Bilateral	Female	59	52	51	B	Cochlear	L – Nucleus CI 512 R – Nucleus CI 24 RE	Cochleitis	92	73
Bimodal	Male	65	46	45	R	Cochlear	Nucleus CI 24M	Unknown	91	83
Bimodal	Male	66	62	35	L	Med-El	Concerto Flex 28	Unknown	83	85
Bimodal	Male	67	64	33	L	Cochlear	Nucleus CI 532	Unknown	79	88
Bimodal	Male	69	67	66	R	Med-El	Synchrony Flex 24	Unknown	86	90
Hybrid	Male	56	54	40	L	Cochlear	Nucleus Hybrid L24	Unknown	86	96
Hybrid	Female	63	50	35	B	Cochlear	L – Nucleus Hybrid L24 R – Nucleus Hybrid S8	Autoimmune sensorinual	65	89
Hybrid	Male	63	48	38	R	Cochlear	Nucleus EAS2	Hereditary	65	79
Hybrid	Female	65	53	50	B	Cochlear	L – Nucleus Hybrid S8 R – Nucleus Hybrid L24	Unknown	58	75
Hybrid	Female	65	62	29	L	Cochlear	Nucleus Hybrid L24	Unknown	75	66
Hybrid	Male	66	64	40	R	Cochlear	Nucleus Hybrid S12	Unknown	93	89
Hybrid	Male	67	65	50	R	Cochlear	Nucleus Hybrid L24	Unknown	53	71
Hybrid	Female	67	64	38	L	Cochlear	Nucleus Hybrid L24	Unknown	55	24
Hybrid	Female	67	55	43	R	Cochlear	Nucleus EAS3 + HA	Unknown	45	67
Hybrid	Female	70	67	65	R	Med-El	Concerto Flex 24	Hereditary	56	91
Hybrid	Male	71	60	42	R	Cochlear	Nucleus Hybrid S12	Unknown	34	72
Unilateral	Female	59	55	19	L	Cochlear	Nucleus CI 422	Unknown	21	19
Unilateral	Male	65	59	55	L	AB	Clarion HiRes 90k	Unknown	59	71
Unilateral	Male	65	58	50	R	AB	Clarion HiRes 90k	Unknown	66	56

S3. StimuliTable S3.1 *Words used in experiments.*

Target	Cohort	Rhyme	Unrelated
batter	battle	ladder	monkey
beak	beet	geek	wave
berry	barrel	fairy	jacket
carrot	carriage	parrot	beagle
chip	chin	whip	boat
coffee	coffin	toffee	badger
dollar	dolphin	collar	hammock
grill	grin	drill	foot
lap	lab	zap	chef
mail	maid	bale	jet
money	mother	honey	wagon
mustard	mustache	custard	penguin
paddle	package	saddle	waiter
pickle	picture	nickel	target
pin	pig	fin	mat
race	rake	face	soup
rain	rays	lane	mime
rope	rose	soap	mule
tower	towel	shower	magic
well	web	bell	ram

Table S3.1 *Carrier phrases used in experiments.*

Carrier Phrases	
here choose the	in this display, choose the image of the
here select the	in this display, find the image of the
here find the	in this display, select the picture of the
this time choose	on this screen, select the image of the
this time select	on this screen, choose the picture of the
this time find	on this screen, find the picture of the
now choose the	for this trial, choose the image of the
now select the	for this trial, find the image of the
now find the	for this trial, select the picture of the
click on the	to keep going, choose the picture of the
this time select ____ on this screen	in this display, select the image of the ____ to keep going
this time choose ____ on this screen	in this display, choose the picture of the ____ to proceed
this time select ____ in this display	in this display, find the picture of the ____ to continue
this time choose ____ in this display	on this screen, choose the image of the ____ to keep going
this time select ____ for this set	on this screen, find the image of the ____ to proceed
this time choose ____ for this set	on this screen, select the picture of the ____ to continue
now click the ____ on this screen	for this trial, select the image of the ____ to proceed
now find the ____ on this screen	for this trial, choose the picture of the ____ to continue
now find the ____ in this display	for this trial, find the picture of the ____ to keep going
now find the ____ for this set	to keep going, choose the image of the ____ on this screen

S4. Pre-Baseline Fixations

Figure S4.1 shows fixations as a function of time after onset of target word, averaged across all correct TCRU trials in the word in isolation condition in the primary experiment; Figure S4.2 shows the same for the replication reported in S1.

Prior to target onset, all items were fixated frequently but roughly equally, as there was no information to guide eye movements. After target onset, both groups fixated the target and cohort; rhymes became active later and to a lesser degree. Relative to NH listeners, CI users showed a slight delay in all fixations. They also had generally higher fixations before the onset of the target, but delayed all fixations after the onset of the target word (relative to NH listeners). The baselining procedure described in the main experiment helps to correct for differences in overall pre-target fixations between groups (and contexts). In both experiments, prior to 0 msec (the onset of the target word) cohort and target fixations were generally similar to the unrelated; however, the enhanced rhyme fixations for CI users are visible in both.

Figure S4.1 Looks to the four object types over time after onset of target word as a function of sentence context in the primary experiment. The dotted vertical line represents the 200ms oculomotor delay.

Figure S4.2 Looks to the four object types over time after onset of target word as a function of sentence context in the replication experiment. The dotted vertical line represents the 200ms oculomotor delay

S5. Analyses of Fit Quality

A critical assumption of the curvefitting approach is that fit quality does not differ substantially across conditions of the model. Here, we present a summary of this for each analysis.

Primary Experiment: Targets.

Logistic fits were good overall, average $R = .998$, across the four cells of the design (CI/NH $\times$ Word in Isolation/Carrier Phrase). A 2×2 mixed ANOVA of the R values showed a significant difference between listener groups, $F(1,40) = 13.83$, $p = .001$ with better fits for NH patients ($M = .9998$) than for CI patients ($M = .9973$). There was also a marginally significant main effect of context, $F(1, 40) = 3.79$, $p = .059$, with better fits, numerically, in the word-in-isolation condition ($M = .9982$) than in the carrier phrase condition ($M = .9977$). There was no significant interaction between the two, $F(1,40) = 2.01$, $p = .164$. Despite these significant differences, it is important to note that the mean differences between condition were less than .01, suggesting only minimal differences.

Primary Experiment: Cohorts

The fits of the jackknifed data were good across conditions and for both CI users and NH listeners, mean $R = .989$. To compare quality of fits across groups we used 2×2 mixed ANOVA of the R values across the four cells. Fit quality did not significantly differ across either group, $F_{jk}(1,40) = 2.67$, $p = .111$, or context, $F_{jk}(1,40) = 0.32$, $p = .572$. There was also no interaction between group and context, $F_{jk}(1,40) = 0.45$, $p = .505$.

Replication Experiment: Targets.

Goodness of fit (correlation) was analyzed with a 2×2 ANOVA examining the effect of listener group and context. This showed a main effect of listener group with CI users ($M = .998$) showing slightly lower quality of fit than NH listeners (.999), $F(1,38) = 14.84$, $p < .001$. There was no significant effect of context, $F(1,38) = 1.68$, $p = .202$. There was no significant interaction between group and context, $F(1,38) = 1.62$, $p = .211$. In all cases, fits were near ceiling.

Replication Experiment: Cohorts

To compare quality of fits across groups we used 2×2 mixed ANOVA of the R values across the four cells. Fit quality did not significantly differ across either listener group, $F_{jk}(1,38) = 3.59$, $p = .066$, or context, $F_{jk}(1,38) = 0.009$, $p = .926$. There was also no interaction between group and context, $F_{jk}(1,38) = 0.01$, $p = .905$.

S6. 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. This was for two reasons. First, the baseline procedure that had been applied successfully to target and cohort fixations led to rhyme fixations exhibiting a non-canonical pattern which could not be fit with the asymmetrical Gaussian commonly used to model competitor looks. Second, CI users—but not NH listeners—showed increased looking to the rhymes during the carrier phrase, before the target was heard. This created an unequal baseline that made it hard to compare groups. We are hesitant to make claims about the cause of this surprisingly increased baseline. Each item in the set was equally likely to be the target on throughout the experiment, we counterbalanced the location of the rhyme on the screen across trials. Nonetheless this peculiar pattern prevents us from implementing our intended analyses.

Instead, here we present several coarser analyses that examine differences in rhyme fixations between context conditions and listener groups. As these were not the planned analyses, they should be treated as exploratory.

For these analyses, we extracted three measures directly from the proportion of fixations over time. These measures were intended—much like curvefit parameters—to describe meaningful properties of the curves, without assuming any particular form (see Rigler et al., 2015). First, we computed: the peak height of fixations to rhymes after subtracting fixations to the unrelated item at each time point. Second, we computed the time at which this peak was reached. Finally, we computed the extent to which the rhyme was active over and above the unrelated competitor (e.g., the proportion of time points at which the rhyme was more active than the unrelated).

These measures do not rely on curvefitting procedures and did not require jackknifing as the cohort analyses in the main text did. Instead, we started by smoothing the proportion of fixations to both rhymes and unrelated items using a 48 ms triangular window to aid in the estimation of a single peak height and time. We then subtracted unrelated fixations from the rhyme fixations for that subject and condition.

Height was defined as the greatest value along this time series, and time as the point in time where this was reached. To calculate the extent of rhyme fixations, we computed the number of time points at which the rhyme item fixations minus unrelated item fixations were greater than .02 (and converted that to a proportion over the entire length of the trial). These measures were then analyzed in standard ANOVAs (similarly to the curvefit parameters). For all measures, the first 250 ms of the time course was ignored to avoid including the unexplained increase in rhyme looks in CI users described above and in the main text.

Primary Experiment Rhymes

Figure S5.1 A shows the smoothed timecourse of rhyme and unrelated fixations for the primary experiment presented in the main text.

Peak height (Figure S5.1B) showed a significant effect of listener group. CI users made more fixations to the rhyme item than NH listeners, $F(1,40) = 13.50$, $p = .001$. No other effect was significant, all $p > .15$. **Peak timing** (Figure S5.1C) showed a significant main effect of context with both listener groups looking to rhymes earlier in carrier phrases than in isolated words, $F(1,40) = 6.75$, $p = .013$. No other effects were significant, all $p > .15$. Rhyme **extent** (Figure S5.1D) also showed a significant main effect of group with CI users showing greater overall rhyme activation than NH listeners, $F(1,40) = 18.10$, $p < .001$, with no other significant

effects, all $p > .10$.

Figure S5.1. A) Rhyme fixations as a function of time after subtracting looks to the unrelated and smoothing, for each listener group and sentence context condition. Panels below indicate individual curvefit parameters; error bars indicated SEM. B) Peak height; C) peak timing (ms); D) extent (proportion of the trial during which fixations to rhymes minus unrelated were greater than .02).

Replication Experiment

We next repeated the same analysis for the replication (Supplement S1). Figure S5.2A shows the smoothed timecourse on which the estimates (S5.2B-D) were based.

Peak height (Figure S5.2B) showed a marginally significant effect of listener group, with CI users making numerically more rhyme fixations than NH listeners, $F(1,38) = 3.54$, $p = .067$. No other effect was significant, all $p > .4$. **Peak timing** (Figure S5.2C) showed a significant main effect of listener group, $F(1,38) = 10.66$, $p = .002$, with CI users reaching their peak rhyme fixations later than NH listeners. No other effect was significant, all $p > .5$. Rhyme **extent** (Figure S5.2D) also showed a significant main effect of group with CI users a longer period of increased rhyme fixations compared to NH listeners, $F(1,38) = 14.54$, $p < .001$. There were no other significant effects, all $p > .4$.

Summary

Across the two experiments, CI users showed evidence of increased rhyme activation, primarily seen in the measure of extent. This suggests that CI users are showing the sustained competitor activation profile that was also observed with cohorts (as described in the main text). Additionally, in the main experiment (and marginally in the replication, S1), CI users showed

Figure S5.2. A) Rhyme fixations as a function of time after subtracting looks to the unrelated and smoothing, for each listener group and sentence context condition. Panels below indicate individual curvefit parameters; error bars indicated SEM. B) Peak height; C) peak timing (ms); D) extent (proportion of the trial during which fixations to rhymes minus unrelated were greater than .02).

evidence of increased peak activation of rhymes relative to NH listeners. This increased rhyme peak is also observed as part of the “wait and see” profile (McMurray et al., 2017). Thus, this adds support to the idea that the CI users exhibited a “wait-and-see” profile (either as part of their response to the experimental task as a whole, or as part of their general profile of listening). The overall pattern of rhyme results supports the conclusions from target and cohort analyses presented in the main text.

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