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REVIEW

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A surgeon-scientist's perspective and review of cognitive-linguistic contributions to adult cochlear implant outcomes

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Abstract

Objective(s): Enormous variability in speech recognition outcomes persists in adults who receive cochlear implants (CIs), which leads to a barrier to progress in predicting outcomes before surgery, explaining "poor" outcomes, and determining how to provide tailored rehabilitation therapy for individual CI users. The primary goal of my research program over the past 9 years has been to extend our understanding of the contributions of "top-down" cognitive-linguistic skills to CI outcomes in adults, acknowledging that "bottom-up" sensory processes also contribute substantially. The main objective of this invited narrative review is to provide an overview of this work. A secondary objective is to provide career "guidance points" to budding surgeon-scientists in Otolaryngology.

Methods: A narrative, chronological review covers work done by our group to explore top-down and bottom-up processing in adult CI outcomes. A set of ten guidance points is also provided to assist junior Otolaryngology surgeon-scientists.

Results: Work in our lab has identified substantial contributions of cognitive skills (working memory, inhibition-concentration, speed of lexical access, nonverbal reasoning, verbal learning and memory) as well as linguistic abilities (acoustic cue-weighting, phonological sensitivity) to speech recognition outcomes in adults with CIs. These top-down skills interact with the quality of the bottom-up input.

Conclusion: Although progress has been made in understanding speech recognition variability in adult CI users, future work is needed to predict CI outcomes before surgery, to identify particular patients' strengths and weaknesses, and to tailor rehabilitation approaches for individual CI users.

Level of Evidence: 4

KEYWORDS
cochlear implants, sensorineural hearing loss, spectro-temporal processing, speech perception, speech recognition

1 | INTRODUCTION

I caught the "research bug," a desire to become a surgeon-scientist, during my Neurotology fellowship. This was when I identified the major clinical question that would form the basis for my own research program: "How do we account for speech recognition outcome variability in adults with cochlear implants (CIs)?" This inadequately answered question was not only directly relevant to my own future clinical practice, but it also opened me to a whole body of fascinating and complementary scientific literature in hearing sciences and cognitive psychology. Together, this clinical motivation and intellectual stimulation supported my pursuit of a surgeon-scientist academic track coming out of fellowship. Of equal importance to these clinical and intellectual motivations, I was fortunate to have early support from my mentors who recognized the value of my clinical questions, and also recognized my potential as a surgeon-scientist, even without a PhD background. The main goal of this invited narrative review is to provide an overview of the work done in our lab to begin to answer this core clinical question related to adult CI users. However, I also wanted to use this opportunity to provide some "guidance points" to individuals in Otolaryngology trying to make it as academic junior surgeon-scientists.

During my fellowship with Dr D. Bradley Welling and Dr Edward Dodson at The Ohio State University, elderly patients would come in to the clinic with severe-to-profound hearing loss, and they would ask, "Doc, will this CI thing help me?" Our typical response was, "Yes, it should. Most people get around 70% sentence recognition in quiet after a CI".[1] And they would say, "But will it help ME?" Our response would be, "Well, you'll almost certainly do better than you do right now!" which was a relatively uninformative answer, because we did not (and still do not) have a good way to predict an individual's ultimate CI outcome. In trying to answer this question by reading the clinical literature, the traditional demographic and audiologic factors we consider - age, duration of deafness, severity of hearing loss, prior use of hearing aids - were altogether relatively weak predictors of outcomes.[1-3] Moreover, these traditional measures do not tell us anything about the *underlying* mechanisms that may serve as targets for intervention.[4]

As a related concern, we had a few older patients who were years out from their CIs, and they were still struggling to understand speech; i.e. they were relatively "poor performers." The device manufacturers would confirm the integrity of the device, and we would order a computed tomography (CT) scan, and the electrode array generally appeared to be in good position. It was clear to me that most of the time the poor performance was not because the device was in the wrong place surgically or it had failed, or even that the mapping was wrong. We would tell the patient that we really did not have any other ideas, and we would encourage the patients to "keep working at it." Clearly, we could not answer the question effectively as to what to do to help a poor performer, or specifically to tailor our rehabilitation approaches for individual patients.[5] In part this was because we did not have clear, specific targets for rehabilitation - individual patient factors that were modifiable and targetable through device programming changes or through therapeutic training regimens (GUIDANCE POINT #1, Table 1.)

Fortunately for me, I identified a mentor at my institution - Dr Susan Nittrouer - an expert in CI outcome variability, but primarily in pediatric CI users. Dr Nittrouer shared some of her papers with me on perceptual attention and weighting of acoustic cues in speech perception,[6,7] and we started wondering how these weighting strategies might impact speech perception abilities among different adults with CIs. The idea was that because CIs deliver temporal (timing) cues more effectively than spectral (frequency-specific) cues, CI users might weight temporal cues more strongly during phoneme (ie, speech sound) categorization (eg, "ba" vs "wa"), but that differences among patients in their weighting strategies might explain differences in word recognition skills. We conducted two studies looking at this,[8,9] and we found that CI patients who demonstrated weighting strategies like normal-hearing (NH) listeners during phonemic categorization tended to perform better on word recognition. Moreover, stronger weighting of spectral cues was not necessarily associated with better discrimination of non-speech spectral changes. Essentially, the brain was telling the ear what to pay attention to, or how to perceptually organize the incoming information, and the brain's attention was not always focused just on what was most strongly conveyed by the CI.

As a budding ear surgeon, I was starting to be impressed by the brain's role in CI outcomes, and the idea that speech recognition is only partly about the signal. Rather, we need to think about speech recognition as information processing, which involves the response of the entire ear-brain system. In other words, both the quality of the signal or the "bottom-up" input, as well as the language knowledge and cognitive skills of the listener or "top-down" processing, contribute to speech recognition outcomes.[10,11] In particular, top-down processes come into play when bottom-up input is degraded.[10] This idea was novel to me at the time, but it was supported by decades of basic research in speech perception.[12-16] Also, as per Dr Nittrouer's work in pediatric CI users, it seemed that the level of phonological processing (ie, access to detailed acoustic-phonetic representations of speech sounds) was a major intersection point of where bottom-up and top-down processing occurs, with her work showing major deficits in development of phonological sensitivity in children with CIs.[17,18] This idea was also supported in adults in two older studies by Andersson and Lyxell from 1998,[19,20] which suggested a deterioration of phonological representations in long-term memory in adults with severe hearing loss. We applied some of the methods Dr Nittrouer had developed to evaluate phonological sensitivity in kids to my adult patients with CIs.[21,22] In brief, we found that a measure of phonological sensitivity explained 35% of the variance in isolated word recognition in adults with CIs.[21] In a follow-up study, we found an audiovisual measure of nonword repetition to predict word recognition in CI users for sentences of varying complexity, both in quiet and in speech-shaped noise.[22] In summary, it appeared that both perceptual attention and phonological sensitivity are contributors to speech recognition outcomes in adults with CIs. (GUIDANCE POINT #2, Table 1.)

Around this time, I was completing my fellowship and began my faculty position at OSU, with a 40%/60% research/clinical

TABLE 1 Ten guidance points to encourage junior Otolaryngology surgeon-scientists

Guidance point	
1	As a surgeon-scientist, identify research questions that are meaningful to you as a clinician, and for which you have both interest and clinical insight. You must capitalize on your clinical training to identify the important questions to inform your research pursuits.
2	As a surgeon-scientist, mentorship is absolutely critical, both from successful clinician-scientists and full-time researchers. Effective mentors will help you to anchor your clinical questions within the pertinent broader basic science literature of your field. These individuals should provide valuable encouragement but also constructive criticism of your plans and should help you remain focused on your goals.
3	Departmental support for you as a surgeon-scientist is paramount to your success. The National Institutes of Health (NIH) want to support "independent investigators." As a surgeon-scientist, it is essential that your department support your time and effort to develop your research program.
4	You will have to apply for lots (and lots) of grants. Start early and apply frequently, starting with foundation grants. You will not get most of them. If you have deficits in your previous research training, the best mechanism will likely be a Career Development Award, which is a mentored research project. This grant mechanism protects a substantial part of your time on your academic appointment for research training and productivity.
5	To boost productivity as a surgeon-scientist, try to incorporate clinical trainees into your projects. To do this, identify projects that seem particularly clinically relevant, and/or target primarily clinical journals for these publications.
6	Just as mentorship is key to your success, development of research collaborations is essential. It is unlikely that your previous training and your ongoing development as a surgeon-scientist are sufficient to make you independently competitive as compared with your full-time research colleagues. You must develop mutually beneficial and trusting collaborative relationships with research partners who will hopefully share their research techniques with you, while you bring clinical perspective and relevance, both to the actual projects/publications and to the grant proposals you develop. However, be careful not to take on too many collaborations that will dilute your progress.
7	Another key in your success as a surgeon-scientist is to surround yourself with people who are smarter than you. Or, if you prefer, people who bring complementary skillsets to yours. You will be amazed at the ideas and expertise other people can apply to your clinical questions. At the same time, be very selective about the people you bring into your lab: the person who oversees the day-to-day of your studies can make or break your progress. (Thank you, Dr Kara Vasil!)
8	Although this narrative seems to follow a logical path, there were many, many instances of distracting projects along the way. Some of these resulted in evident productivity, including publications. However, others provided a distraction from prioritized goals. It is essential to identify projects that align with your goals, and say no to others.
9	Try to bring your research findings back to your clinical population. This may be more difficult to find funding to support, but it is why you became a surgeon-scientist to begin with.
10	Start working on your next grant proposal well before the previous grant period is up. Plan ahead, expecting that successful R01 funding will take at least one or two grant proposal resubmissions.

appointment. (GUIDANCE POINT #3, Table 1.) I was reading more about top-down functions in patients with hearing loss and came across work by Dr Larry Humes,[23] as well as an article by Dr Michael Akeroyd,[24] which was a review of studies of working memory (WM) and cognitive processes as contributors to speech recognition in adults with milder degrees of hearing loss and/or hearing aids. I began thinking using a very simple model (Figure 1), where there are four main contributing domains to speech recognition variability: perceptual organization and language skills, along the lines of my previous projects with Dr Nittrouer, but also auditory sensitivity - or how well the signal is delivered by the CI - as well as cognitive factors. More broadly, these domains could be simplified just to "bottom-up" auditory sensitivity and "top-down" processes, encompassing the other three domains. Although this model does not say anything about mechanisms, there is an idea that I tried to convey, related to studying variability and individual differences and how they might relate to intervention targets. This is a hypothetical model, and Figure 1 shows three hypothetical examples. In each, the big circle in the middle shows the speech recognition outcome of interest. The size of the portion of this circle dedicated to each predictor domain suggests how much of the outcome variability is associated with that predictor domain. If that predictor area does not relate substantially to outcomes, then we do not care all that much about it for the purposes of explaining outcome variability. Second, the size of each predictor domain circle represents how much that predictor domain actually varies among patients. If that predictor circle is tiny, that is, the factor does not vary much among patients, then it is very unlikely that it is something that we can address clinically (eg, to make changes to get poor performers in that domain performing like excellent performers), without an entire shift in CI technology. So, again, if the predictor domain circle is small, we should not focus very much on that domain in solving our outcome variability problem, and it will not make a very good target for rehabilitative intervention.

To apply this simple model, aimed at identifying what measures within each of those four predictor domains would be associated strongly with speech recognition outcomes, we first needed to identify speech recognition outcome measures that would show broad variability across CI participants. This consideration led me to select

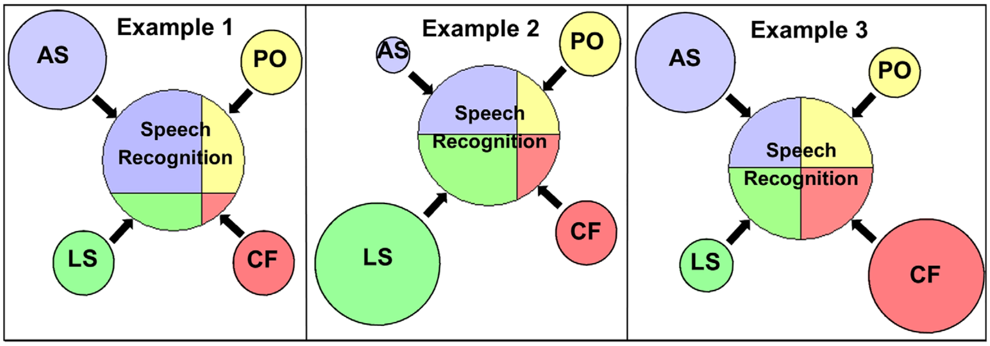

FIGURE 1 Hypothetical examples of simple model showing four potential contributing domains to speech recognition variability: Auditory Sensitivity (AS); Perceptual Organization (PO); Linguistic Skills (LS); and Cognitive Factors (CF). In each example, the big circle in the middle represents speech recognition. The size of the portion of the circle dedicated to each predictor domain represents how much of the outcome variability is attributable to that predictor domain. The size of the smaller circle for each predictor domain represents how much variability exists among individuals in that predictor domain. If the predictor domain does not relate substantially to outcomes, or if it does not demonstrate variability among individuals, then it is not highly useful for the purposes of explaining outcome variability or for identifying potential targets for intervention. Example 1: AS explains the majority of variability in speech recognition, with large individual variability in AS. This model suggests that improving AS to the level of the best users should be a primary objective in optimizing outcomes. Example 2: AS again explains a large portion of variability in speech recognition, but minimal individual variability is seen in AS. Large individual variability is seen for LS, which also accounts for a large portion of variability in speech recognition. This model suggests that perhaps overall AS should be a focus of future implant research, but that LS should be targeted to optimize outcomes for patients with current implants. Example 3: All four domains explain equal portions of variability in speech recognition, but the greatest amount of individual variability is seen in AS and CF. This model suggests that targeting AS and CF should be our goal in optimizing outcomes for current CI users, as these are the factors that show the most individual variability

the measures of speech recognition that I have been using the past few years. These are measures of word and sentence recognition in quiet, at least to begin with. For each of these measures, adult CI users were expected to show broad ranges of performance among listeners without major ceiling or floor effects. I also selected nonclinical measures with which patients would not be familiar. These included the CID-W22 isolated words,[25] and three types of sentences[1]: the IEEE or Harvard Standard sentences,[26] which are relatively complex and semantically meaningful, spoken by a single male talker[2]; the Harvard Anomalous sentences,[27] which were developed from the Harvard Standard sentences but lack semantic context, so they should rely more heavily on bottom-up processing; and[3] the PRESTO sentences,[28] which are complex sentences spoken by lots of different talkers, which results in increased cognitive load.

Of the four predictor domains of the model, so far we had shown that the linguistic skill of phonological sensitivity seemed to explain some variability in speech recognition abilities.[21] We had also included measures of receptive and expressive vocabulary, but neither of these appeared to be strongly associated with word recognition abilities.[8,9] Under the domain of perceptual organization, this concept broadly relates to the process of structuring incoming sensory information into coherent perceptual units. In this domain, I already discussed our work on perceptual organization with acoustic cue-weighting, which did predict word recognition in CI users.[8,9] I also incorporated a measure of perceptual closure called the Fragmented Sentences test where the participant is shown these visually degraded sentences on a computer screen for about a second and is asked to read them aloud. Interestingly, scores on this task appear to predict some variability in sentence recognition for NH participants listening to vocoded sentences (ie, sentenced processed to simulate the spectral degradation of CI processing), but less so for CI users listening to speech materials.[29]

Around that time, I began collaborating more extensively with Dr David Pisoni at Indiana University, who is an expert in cognition and cochlear implantation, and we started exploring cognitive functions more broadly and their roles in speech recognition. That was also about the time that two other important mentors/collaborators, Dr Derek Houston and Dr Irina Castellanos, joined our department at Ohio State, bringing a hefty dose of Psychology to our Neurotology division. My focus at the time was to identify *visual* cognitive measures that would be appropriate for use in my clinical population of older adults with hearing loss. This goal originated because audibility concerns could impact our ability to assess the cognitive functions of patients with hearing loss (with or without CIs) using traditional auditory or audiovisual measures of cognition. We began implementing several visual cognitive measures to test their associations with speech recognition outcomes in about 50 adults with CIs. These cognitive measures have included assessments of inhibition-concentration, processing speed, nonverbal reasoning, working memory, and verbal learning and memory. I will summarize findings from a few of them that have been particularly high-yield with regard to their associations with word and sentence recognition outcomes in adult CI users, and that also demonstrate a lot of variability among individual patients. Importantly, scores of most of these visual cognitive measures are not highly inter-correlated, so we have typically considered them independently in our analyses. (GUIDANCE POINT #4, Table 1.)

First, during speech recognition, lexical competitors are activated and incorrect word selections must be inhibited. Additionally, masking sound sources must often be ignored when listening to speech in noisy situations. A visual measure of inhibition-concentration is the visual Stroop task.[30] In this task, the participant is presented color words on a screen and is asked to inhibit word reading in favor of responding with the color of the word. In the case of an incongruent word and color, the correct response requires inhibiting an over-learned skill, which is to read the word. Quicker correct responses suggest better inhibition-concentration. Using this task, we have found correlations with several different measures of sentence recognition, and the ability to use sentence context, in speech-shaped noise and/or in quiet.[31,32]

Another cognitive function related to speech recognition is information-processing speed. We have used a visual neurocognitive measure of speed, specifically speed of lexical and phonological access, the Test of Word Reading Efficiency (TOWRE-2[33]). Here the participant has to read a list of words and a list of nonwords as quickly and accurately as possible in 45 seconds. In short, speed of lexical access may provide some explanatory power for variability in sentence recognition in CI users.[34]

Similarly, we have used a visual test of nonverbal reasoning or fluid intelligence, the Raven's Progressive Matrices,[35] in which the participant has to problem-solve and figure out which item fills in the blank spot in the pattern above. This measure has been high-yield in its relation to word and sentence recognition outcomes in adult CI users. Our findings showed that this 10-minute test of nonverbal reasoning predicted 10% to 15% of the variance in sentence recognition for Harvard Standard sentences, as well as for PRESTO sentences with high-talker variability.[36]

We also applied a visual measure of verbal learning and memory, a modified version of the California Verbal Learning Test (CVLT-II[37]), to determine its associations with speech recognition in adult CI users.[38] This is a free recall task of 16 words from different semantic categories that are repeatedly presented five times, along with an interference list. This measure provides a number of primary and process measures related to learning, storage, and retrieval strategies. In that study, we identified a measure of proactive interference, which relates to how much previously presented words impact learning of new words, as correlating with speech recognition performance in CI users. More recently, we demonstrated that a preoperative measure of learning slope over the first five list repetitions can actually predict speech recognition abilities after 6 months of CI use (in preparation).

Working memory (WM) has received a lot of attention in patients with hearing loss, as reviewed initially by Akeroyd in 2008. Working memory is a limited-capacity system responsible for temporary storage and processing of information for use in the moment.[39,40] Our group has been using three measures of WM. First is a visual Digit Span where digits are shown one at a time, and the participant has to recreate the sequence on a touchscreen. The other two are similar span tasks for easily named objects (Object Span), and for symbols that cannot be easily labeled (Symbol Span). Interestingly, so far our measures of working memory have only been weakly associated with speech recognition outcomes in CI users.[41] However, there may be two reasons for this: First, these simple span measures tap primarily into the storage component of working memory, and much less into processing. That is, they are relatively simple tasks primarily of short-term memory and likely are loading mostly the phonological loop of WM storage rather than the central executive responsible for processing. Second, it seems that the sensory modality likely plays a role. That is, testing WM using auditory tasks seems to relate more strongly to speech recognition than testing WM with visual stimuli.[42] (GUIDANCE POINT #5, Table 1.)

Clearly, though, top-down cognitive and language measures do not explain everything. We still have to be able to measure the bottom-up quality of the signal delivered by the CI, which we broadly refer to in the model as "auditory sensitivity." We have been using a variety of auditory sensitivity measures to try to assess spectral and temporal processing abilities. In our set of about 50 adult CI users to date, we have obtained thresholds from the Spectral-Temporally Modulated Ripple Test (SMRT) by Drs. Aronoff and Landsberger.[29,43] More recently, we have been collaborating with Dr Valeriy Shafiro at Rush University to collect data using his task of stochastic frequency modulation for dynamic spectral patterns,[44] along with amplitude modulation detection (AMD) thresholds using a task developed at University of Washington by Dr Jay Rubinstein's group[45] in a smaller number of CI users. So far, Table 2 shows our findings of relations of auditory sensitivity with our speech recognition measures in experienced CI users. Both spectral tasks appear to be strong predictors of outcomes, but this is less so for the amplitude modulation detection measure of temporal processing. (GUIDANCE POINT #6, Table 1.)

TABLE 2 Pearson bivariate correlations among speech recognition measures and "bottom-up" sensory measures in experienced adult cochlear implant users. SMRT: Spectral-Temporally Modulated Ripple Test; AMD: Amplitude Modulation Detection test. *r* and *p* values are bolded where $P < .05$

		SMRT threshold	Stochastic Frequency Modulation threshold	AMD threshold
CID words (% correct)	*r*	**0.594**	**−0.51**	−0.329
	p	**< .001**	**.018**	.157
	N	49	21	20
Harvard Anomalous sentences (% words correct)	*r*	**0.635**	**−0.649**	−0.368
	p	**< .001**	**.003**	.121
	N	45	19	19
Harvard Standard sentences (% words correct)	*r*	**0.478**	**−0.505**	−0.213
	p	**.001**	**.027**	.381
	N	45	19	19
PRESTO sentences (% words correct)	*r*	**0.609**	**−0.573**	−0.279
	p	**< .001**	**.010**	.247
	N	45	19	19

So far, we have identified a number of top-down and bottom-up factors across several domains that contribute to, or are at least associated with, CI speech recognition outcomes. How does this help us to address our main clinical question: “How do we explain speech recognition outcome variability in adults with cochlear implants (CIs)?” Again, our traditional demographic and audiologic measures explain less than half of the variance in outcomes.[2] We would predict that a combination of those traditional measures along with our bottom-up and top-down measures would be more highly explanatory. We began to investigate this combination using partial least squares (PLS) regression to identify the most valuable predictors of our speech recognition measures, led by Dr Jeff Skidmore.[46] Using this approach, predictors were assigned Variable Importance in Projection (VIP) scores. Those predictors with the highest VIP scores were entered into regression models to see how much of the variance in the outcomes could be predicted by the sequential addition of each predictor. Results showed that with the inclusion of a combination of 14 demographic, bottom-up, and top-down measures, we were able to explain about 80% of the variance in sentence recognition outcomes. This result suggests that we are making progress, but we still have a ways to go to be able to explain outcomes more accurately. We posit that one of the reasons for our inability to completely explain outcomes is because these bottom-up and top-down processes interact in complex ways, and we need to be able to account for those interactions in our predictive models.

Our second, but related, clinical question was as follows: “Why are some CI patients 'poor performers'?” To start getting at that, we used an extreme groups analysis based on PRESTO sentence recognition scores, the high talker variability sentences. This was led by Dr Terrin Tamati.[47] (GUIDANCE POINT # 7, Table 1.) A discriminant analysis was performed to determine if the “high performers” on PRESTO differed in some characteristic ways from the “poor performers.” We determined that the high- vs low-performance distinction on PRESTO sentences is likely driven mostly by differences in spectral resolution on SMRT, and secondarily by nonverbal reasoning. The poor SMRT participants tended to be PRESTO poor-performers, while the PRESTO high-performers showed a much broader range of SMRT scores. In a follow-up study on a larger (but overlapping) sample of adult CI users, we determined correlations of cognitive functions with speech recognition among low-, intermediate-, and high-SMRT CI users (in preparation). Visual measures of cognition were associated with speech recognition outcomes in the intermediate- and high-SMRT groups, but less so in the low-SMRT group. Together, these findings suggest that there is a threshold level of spectro-temporal processing below which top-down cognitive-linguistic skills cannot help the listener compensate for the poor quality of the signal, and those individuals with poor bottom-up skills will be poor performers regardless of how good their cognitive functions are. However, above that threshold, CI users may rely on a range of cognitive compensation mechanisms to understand speech. (GUIDANCE POINT #8, Table 1.)

This final concept, that bottom-up and top-down functions interact, leads to a third important clinical question: “How do we optimize CI speech recognition outcomes, particularly for 'poor performers'?” Current approaches to auditory training for individuals with hearing loss are typically “one-size-fits-all” and are not highly effective.[48] Optimizing outcomes likely starts with being able to translate the lab findings to develop bottom-up/top-down profiles for individual patients in the clinic, and then use that information to target specific deficits during rehabilitation. This idea has motivated the development of personalized and comprehensive auditory rehabilitation (AR) approaches for our adult CI users at OSU, led by Dr Christin Ray, a PhD Speech-Language Pathologist. Essentially, Dr Ray is in the early phases of using similar assessments in the clinic to develop these bottom-up/top-down types of profiles for individual patients in the clinic. From these profiles, she tailors rehabilitation approaches for those individual patients to target deficits and capitalize on strengths. We have some proof-of-concept evidence that clinician-guided AR that targets both bottom-up and top-down processing can improve speech recognition and quality of life for experienced CI users,[49] and maybe for new CI users.[50] We plan to study the clinical outcomes as a result, predicting that individually tailored approaches based on bottom-up/top-down profiles will help us to develop more effective AR approaches. Ideally, in turn, determining the impact of these AR approaches will then inform us regarding which bottom-up and top-down processes are malleable and can be impacted by AR, which will further help us to understand the mechanisms that underlie speech recognition in CI users. (GUIDANCE POINT #9, Table 1.)

We still have a lot of work to do. (GUIDANCE POINT #10, Table 1.) What is really needed is a longitudinal prospective study that enrolls pre-operative CI candidates and examines changes in their speech recognition, bottom-up, and top-down processing during the first 2 years after implantation, which is the time frame during which most adults with CIs reach a plateau in speech recognition performance.[51] This study design will allow us to develop a definitive set of pre-operative measures that can be used to predict speech recognition outcomes to be able to counsel our patients better. This approach will also allow us to develop a better understanding of the mechanisms that underlie changes in processing during the perceptual learning that occurs after implantation. Also, there are limitations in interpreting our current psychophysical measures of bottom-up sensitivity, because it appears that cognitive functions may impact how well people perform on these measures.[52,53] Thus, a future direction is incorporation of more objective electrophysiological measures of bottom-up processing, including tests of electrocochleography (ECochG[54]) and electrical compound action potentials (ECAPs[55]). Lastly, we need to develop individualized bottom-up/top-down profiles for our patients and to test personally tailored AR approaches for those patients based on their individual profiles.

In conclusion, we are making some progress in solving the problem of understanding outcome variability in adult CI users, which relates to both bottom-up and top-down processing abilities and their interactions. We have a great deal more work to do to understand how we can use assessments of those abilities specifically to predict outcomes for individual patients we see in the clinic, how to identify particular deficits in an individual patient who is struggling with a CI, and how to tailor AR approaches that are specific to that patient. As a surgeon-scientist, I continue to be motivated by these clinical questions, recognizing that answering these questions will depend upon a collaborative team of researchers, clinicians, and clinician-scientists who bring complementary skills to optimize outcomes for our adults with CIs.

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CONFLICT OF INTEREST

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