Cognitive compensation of speech perception in hearing loss: How and to what degree can it be achieved?

DENIZ BAŞKENT[1,2*], PRANESH BHARGAVA[1,2], JEFTA SAIJA[1,2], JEANNE CLARKE[1,2], MICHEL R. BENARD[1,3], CARINA PALS[1,2], ANASTASIOS SARAMPALIS[2,4], ANITA WAGNER[1,2], ETIENNE GAUDRAIN[1,2,5]

[1] *University of Groningen, University Medical Centre Groningen, Department of Otorhinolaryngology/Head and Neck Surgery, Groningen, The Netherlands*

[2] *University of Groningen, Graduate School of Medical Sciences, Research School of Behavioural and Cognitive Neurosciences, Groningen, The Netherlands*

[3] *Pento Speech and Hearing Center Zwolle, Zwolle, The Netherlands*

[4] *University of Groningen, Department of Psychology, Groningen, The Netherlands*

[5] *Lyon Neuroscience Research Center, Auditory Cognition and Psychoacoustics, CNRS, Université Lyon, Lyon, France*

In daily life, speech is often degraded due to environmental factors, but its perception can be enhanced using cognitive mechanisms. Such compensation not only relies on increased cognitive processing (listening effort), but also makes use of context, linguistic knowledge and constraints. In hearing impairment, the speech signal is additionally and intrinsically degraded due to loss of audibility and/or suprathreshold deficiencies. In cochlear implants, the signal transmitted is spectro-temporally degraded. Hence, it has not been clear if hearing-impaired individuals and hearing-device users can as successfully use the cognitive compensation mechanisms, due to the interactive effects of these degradations with aging and hearing device front-end processing. The speech intelligibility tests are not capable of characterizing the cognitive compensation mechanisms. In our research, reviewed here, we have employed new approaches (phonemic restoration, dual-task paradigm, eye tracking, verbal response times) to answer this research question. Our results have shown that there is a fine balance between the speech degradations and their top-down compensation. This can be broken in advanced degrees of hearing impairment or due to inadequate device settings. With degraded speech, sentential context can still be used. Yet, this may come at the cost of delayed processing, likely drawing on more cognitive resources then timely integration of semantic information by NH listeners. Aging does not always have to have a negative effect; long-term linguistic and lexical knowledge may be successfully employed to achieve compensation. These findings indicate that new measures of cognitive processes need to be developed and used in clinics and device development, to comprehensively capture speech comprehension abilities and to improve diagnostic and rehabilitation procedures and tools.

---

*Corresponding author: d.baskent@umcg.nl

INTRODUCTION

Understanding speech under ideal conditions presents little ambiguity. As a result, lexical activation is automatic, requiring minimal cognitive processing for the decoding of the message (e.g., Marslen-Wilson & Welsh, 1978). In real life, listening conditions are hardly ideal. Speech signal is usually distorted by poor room acoustics, masked by background sounds, and heavily reduced in acoustic speech cues. Resolving the increased ambiguity due to these factors calls for cognitive mechanisms to be engaged (e.g., attention, use of grammatical and syntactical constraints, context). This disambiguation must be accomplished in a rapid pace so that the conversation may continue. As a result, top-down mechanisms play an important role in compensating for factors complicating daily life speech communication (Mattys et al., 2012), especially for hearing-impaired (HI) individuals. Similar to the external or articulation-related factors listed above, hearing impairment is another factor that can negatively affect speech intelligibility. This may be the direct result of missing speech cues due to reduced audibility, or as the consequence of distortions due to supra-threshold factors related to hearing impairment. Hearing devices can also change the speech signals, for example, due to front-end processing, or due to the limitations of the speech transmission to the auditory nerve, such as the case for cochlear implants (CIs). A further compromise may occur due to age-related changes in cognitive processes (Salthouse, 1996).

Cognitive processes of speech perception have been of special interest to our group. The speech intelligibility test commonly used for speech audiometry in the clinic provides only a partial picture of an individual's speech communication skills. This score only provides one number for speech perception, tested under ideal conditions of one (clearly articulated) word or sentence presented at a time, without revealing any of the underlying processes of the comprehension. In our research, we have employed new approaches to explore if the HI individuals can still benefit from top-down compensation mechanisms, or if the cognitive processes of speech comprehension would differ for them. If latter, this difference could be one of the factors contributing to difficulties HI listeners experience in perceiving speech in noise. However, because such differences are not yet fully studied and only poorly understood, no adequate solutions can yet be offered.

TOP-DOWN RESTORATION OF INTERRUPTED SPEECH

In perception, pieces of information that belong to a common object are segregated (from others), and grouped together (Wagemans et al., 2012), making perception easier and more efficient. This tendency for forming a perceptual object from perceived pieces can also enhance perception of degraded speech. As early as in the 1950s, Miller and Licklider (1950) observed that interrupted speech remained highly intelligible for a wide range of interruptions (from very slow interruptions of 0.1 Hz to as high as 10 kHz), despite a large amount of missing speech information. This is partially due to the acoustic redundancy in speech signals, where speech cues are coded in multiple ways (Best et al., 1981; Lippmann, 1996), and the linguistic redundancy, which comes from rich sentential context (Gillette & Wit, 1998).

Hence, the brain can overcome missing speech information with top-down restoration. The restoration can be so strong that, under specific circumstances, listeners may not even be aware of the missing part of a speech signal. Warren (1970), for the first time, demonstrated this with speech with a silent gap that was filled with a coughing sound. While such non-speech filler does not contribute to speech information, it nonetheless serves to create a continuity illusion, due to the strong grouping tendency of the human perceptual system to form an object.

Adding a filler (usually a broadband noise) in the gaps of interrupted speech can also lead to an increase in intelligibility (Fig. 1). In this case, the filler noise hides the spurious cues from the silent gaps that can be wrongfully attributed to an incorrect word. It also increases the ambiguity, perhaps also increasing reliance on context cues. The resulting intelligibility improvement provides a measure of phonemic restoration benefit, which we have frequently used in our research to quantify the top-down compensation with hearing impairment.

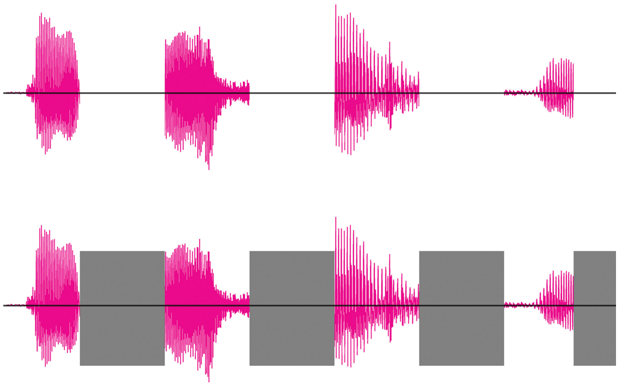

Fig. 1: Speech stimuli used in phonemic restoration experiments.

Top-down restoration and hearing impairment

In one of the earliest studies we have conducted, we have measured phonemic restoration effect with NH, mildly HI, and moderately HI individuals. Our results (Fig. 2, left panel) showed that while mildly HI individuals could benefit from phonemic restoration, moderately HI individuals could not (Başkent, 2010; Başkent et al., 2010). This observation implies that in mild HI (and with adequate amplification) top-down mechanisms can still be effectively used. However, as the degree of hearing impairment increases, and perhaps also as a result of suprathreshold factors coming into play (as it can happen in moderate to severe hearing loss), these mechanisms seem to lose their effect.

Top-down restoration and aging

Because many HI individuals tend to be older, we have also studied age effects on phonemic restoration (Saija et al., 2014). Previous research had shown a negative effect of age on perception of interrupted speech with silent intervals (Bergman et al., 1976), mostly attributed to the age-related decline in temporal processing (Gordon-Salant and Fitzgibbons, 1993). However, it was not clear if older listeners could still effectively use the top-down restoration mechanisms. Our expectations were twofold. If the age-related decline in cognitive factors such as processing speed or working memory is an important factor, age would work against the restoration ability. If the cognitive and linguistic skills, such as long-term world and linguistic knowledge, as well as good use of context (Pichora-Fuller, 2008; Salthouse, 2004), are important factors, age should not negatively affect restoration ability. Our results showed that phonemic restoration benefit was just as strong as with younger group (Fig. 2, right panel), supporting the latter. Benard et al. (2014) later confirmed that linguistic skills indeed seem to play an important role on perception of interrupted speech in general. If these findings can be corroborated with further studies, this is good news for older and HI population, as linguistic knowledge and skills can be improved with proper training.

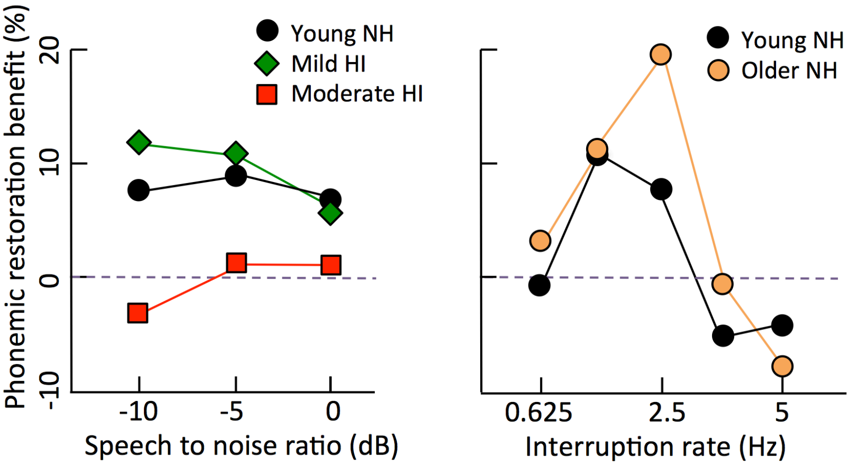

Fig. 2: Phonemic restoration benefit, shown for the effect of hearing impairment, a function of the filler noise level (left panel; adapted from Başkent et al., 2010), and shown for the effect of aging, as a function of interruption rate (right panel; adapted from Saija et al., 2014).

Top-down restoration and hearing devices

In CIs, the speech signal is directly delivered to the auditory nerve via electric stimulation. This signal, mainly limited by the electrode-nerve interface, retains gross spectral information and temporal envelope, while all spectro-temporal fine structure is lost. The re-learning of the degraded speech requires substantial adaptation following the surgery (Lazard et al., 2014). While many CI users reach acceptable speech intelligibility in quiet, this is not universal, with large variation across individuals (Blamey et al., 2013). Further, perception of speech in complex environments with interfering background sounds remains a challenge (Friesen et al., 2001; Stickney et al., 2004).

As CI users have to cope with the degraded speech on a daily basis, top-down restoration mechanisms would especially be important for them. However, it is not clear if they could manage to benefit from top-down restoration given the impoverished CI speech. Earlier studies had shown CI users have difficulty with perception of interrupted speech (Bhargava et al., 2015; Chatterjee et al., 2010; Nelson & Jin, 2004), and data from acoustic CI simulations implied no restoration benefit (Başkent, 2012). Data from actual CI users, however, presented a more complicated picture (Bhargava et al., 2014). On average, CI users did not show phonemic restoration benefit in conditions where such benefit was observed in NH, as was expected from simulations. However, individual data showed that CI users with highest speech intelligibility scores also showed restoration benefit (Fig. 3, left panel). The causality in these data is not clear, i.e., are these good users because they use their top-down mechanisms better in general or is there a third factor that makes them good user overall? Yet, the data hint at the large variation in the use of top-down mechanisms within hearing-device users, and the importance of investigating the individual differences in such data.

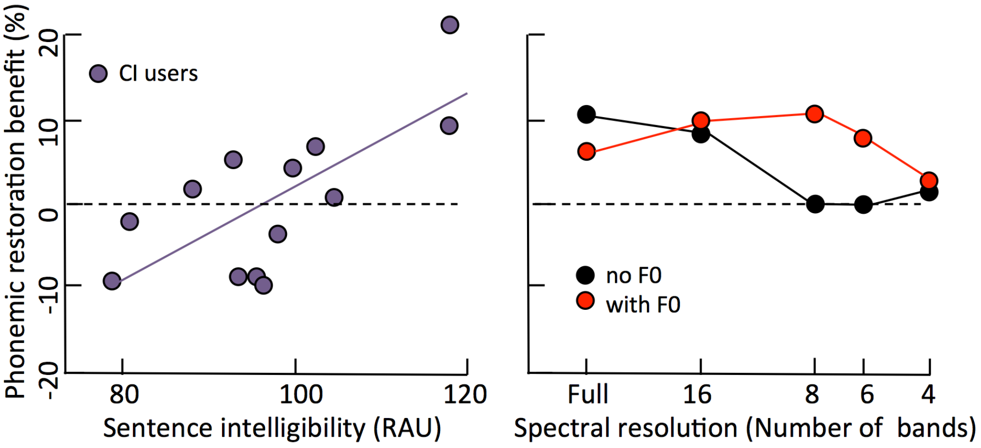

Fig. 3: Phonemic restoration benefit shown for individual CI users, as a function of baseline sentence identification score (left panel; adapted from Bhargava et al., 2014), for NH listeners tested with an acoustic CI simulation, as a function of number of spectral bands (right panel; adapted from Clarke et al., 2015).

The voice pitch, namely F0, is a very important cue for perceptual organization in general, and for grouping speech segments. However, this cue is only weakly delivered in CIs (Moore and Carlyon, 2005), perhaps contributing to reduced ability to separate speech from background sounds. As an exploration into the effects of device features on restoration benefit, we have used TANDEM-STRAIGHT (Kawahara and Morise, 2011) to produce noise-excited speech, a new approach to acoustic CI simulations, where we could simultaneously vary the spectral resolution and the presence/absence of F0 (Clarke et al., 2015). Our results with NH listeners showed a highly interactive picture (Fig. 3, right panel). When spectral resolution was high (16 bands), where there was restoration benefit, or low (4 bands), where there was no benefit, absence or presence of F0 did not seem to matter. However, in the mid ranges of spectral resolution (6 and 8 bands), where the actual CI users functionally perform similarly to (i.e., Friesen et al., 2001; Bhargava et al., 2015), absence/presence of F0 seems to play a significant role in benefiting from restoration. Hence, the simulation results are in line with the observations from actual CI users, indicating that the device features can affect how a CI user can benefit from top-down restoration.

LISTENING EFFORT

Perception of degraded speech requires allocating more cognitive resources, especially that of working memory (Baddeley & Hitch, 1974), i.e., an increase in listening effort. This is a useful mechanism for maintaining a high-level intelligibility. However, it can also come at the cost of affecting other cognitive processes, such as remembering what is said (Rabbitt, 1968), as cognitive resources are limited (Kahneman, 1973).

Clinical diagnostic tools in audiological practice currently only include speech audiometry, which reveals an intelligibility score. While this score shows the capacity of the HI individual or hearing-device user for recognizing speech, it does not reveal the underlying cognitive processes. Some patients complain that they suffer from listening fatigue, likely a result of extended duration of increased listening effort (Hornsby, 2013; McGarrigle et al., 2014). However, no clinical tool currently exists to quantify listening effort in clinical settings, other than attempts made in research (Mackersie & Cones, 2011; Rudner et al., 2011; Sarampalis et al., 2009; Zekveld et al., 2010), despite a long history of general use of response times in sensory perception and speech recognition in general (Hecker et al., 1966; Koga & Morant, 1923).

Recently, we have conducted a number of studies to show that simple audiometric speech scores may fail to capture the cognitive processes and listening effort needed for understanding speech via a CI. In an earlier study (Pals et al., 2012), we have used a dual-task paradigm, where the participants had to simultaneously conduct a secondary visual task while also conducting the primary task of speech intelligibility. Based on the idea of limited cognitive resources and an interaction of the two tasks, this way one can measure the changes in the effort required for differing speech intelligibility conditions in the response times of the second task. We have used an acoustic CI simulation to change the quality and intelligibility of speech, by changing the number of spectral channels. As the number of channels increased, intelligibility, measured by accuracy, increased, and listening effort, measured by response time to the secondary task, decreased (Fig. 4, left and right panels, respectively). However, while intelligibility plateaued at 6 channels, listening effort continued to improve to 8 channels. Hence, while a clinical speech audiometry would indicate the same speech performance for both 6- and 8-channel settings, only the listening effort measure would indicate the additional benefit.

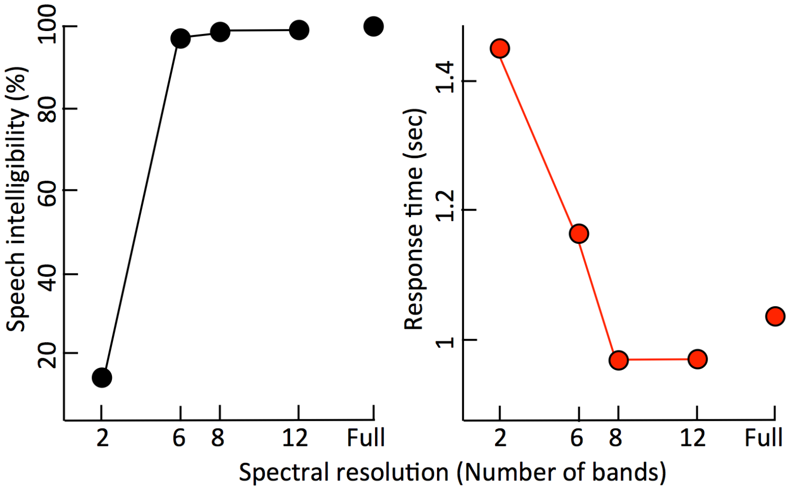

Fig. 4: Speech intelligibility from primary task (left) and response time from secondary task (right), shown as a function of the number of spectral channels of the acoustic CI simulation. Adapted from Pals et al. (2013).

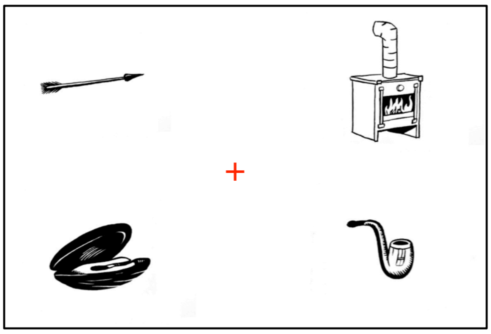

Fig. 5: Visual world paradigm screenshot used by Wagner et al. (2015) in measuring gaze fixations as a quantification of time course of speech comprehension.

CONTEXT EFFECT AND COGNITIVE PROCESSES

Recently, we have used an eye tracker for an online measure of lexical decision making (Wagner et al., 2015). Specifically, we have measured gaze fixation, to quantify the time course of speech perception, and pupil dilation, to measure listening effort. Here, again using CI simulations, we have asked the questions if sentential context can help resolving ambiguity in word identification, despite the degradations of CI speech, and if yes, would the time course be the same. The gaze fixations were measured using visual world paradigm (Dahan et al., 2007), where the target word of a sentence ("pijp (pipe)") would be presented on the screen (Fig. 5), along with a word similar in sound ("pijl (arrow)"; phonological competitor), a word similar in meaning ("kachel (stove)"; semantic distractor), and an unrelated distractor ("mossel (mussel)"). When there is no context, the main confusion would come from the phonological competitor. When there is context, the confusion would come from the semantic distractor.

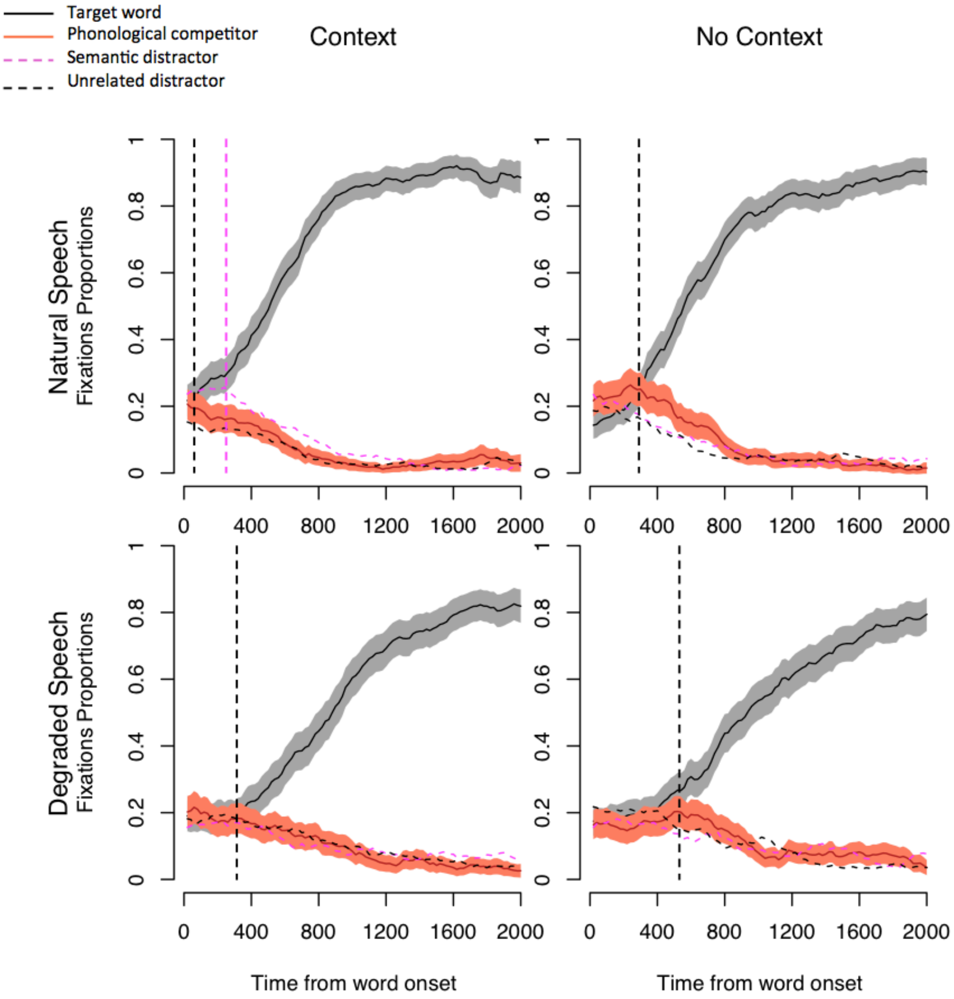

Fig. 6: Gaze fixations, as measured by a visual world paradigm, are shown for high- and no-context sentences (left and right, respectively), and for natural and degraded speech (top and bottom, respectively). Adapted from Wagner et al. (2015).

Fig. 6 shows the data from gaze fixations, with high- and no-context sentences (left and right panels, respectively), and without and with acoustic CI simulation (top and bottom panels, respectively). The most important data is the disambiguation point (marked with vertical dashed lines), where the target fixation (shown in grey) splits from the rest of the fixations. In natural speech, the disambiguation occurs much faster with context than with no context (comparison of left to right panels on top). With degraded speech, a similar effect is observed, but the disambiguation point comes at a significantly later time (lower panels). This observation implies that context is still helpful in dissolving the ambiguity despite the degradation. However, the caveat is that the semantic distractor is not showing an effect in degraded speech (indicated by pink dashed line overlapping red line and black dashed line in the 3 panels other than the top-left one) while it does in natural speech (top-left panel, also indicated by the vertical pink dashed line). This implies that the semantic integration is not efficient, and considerably delayed, which likely would cause problems in real-life fast conversations. In short, while in NH listeners the use of semantic integration leads to a relief of resources needed for lexical access (or word finding), this source of relief is not functioning when processing degraded speech. As a result, the degraded speech cues at the early stages of speech processing seem to affect the later stages, possibly (and negatively) affecting higher-level functions. For example, the delayed processing will likely draw more on memory resources relative to NH listeners.

Currently, we are systematically investigating simpler measures that can be used in clinics, for example, simple measures of verbal response times (Pals et al., 2015). While dual-task paradigm is proven a robust measure of listening effort, it is relatively difficult to set up. The two tasks have to interact just the right way. If one is too easy or too difficult, no effect will be observed. Further, a dual task can be too taxing for an older HI person. Similarly, eye tracking and pupillometry are robust methods for quantifying cognitive mechanisms of speech perception and listening effort. While these require expensive hardware, for populations where behavioural measures may be difficult to apply (such as in very young children), eye tracker still remains as a good potential option.

CONCLUSIONS

Overall, there seems to be a fine balance between the amount of bottom-up speech degradations and the effectiveness of the top-down compensation mechanisms. Our studies have shown that this balance can be broken in hearing impairment and/or use of hearing devices, making this population extra vulnerable in real-life noisy listening environments. There also is a strong effect of age, an important factor due to many HI individuals tending to be older, however, this effect is not easily predictable. While in some situations, such as perception of interrupted speech, age has a negative effect, in some others, such as phonemic restoration, there is no such effect. The latter is a very positive finding, as we have attributed the lack of age effect to vocabulary and linguistic knowledge that seem to be retained in advanced age, and these are entities that can potentially be improved with proper training. Hence, our results also indicate potential training tools for improving perception of degraded speech in HI individuals (e.g., Benard and Başkent, 2014).

Such complex and interactive effects of cognitive factors in speech perception with hearing loss cannot be readily captured with the existing traditional speech tests used in the audiological practice. Measures for online speech processes and for cognitive factors may reveal more to speech comprehension and communication, especially in real-life conditions, than intelligibility scores alone. New methods (such as proposed by Pals et al., 2015; Wagner et al, 2015; Winn et al., 2015; Zekveld et al., 2010) need to be incorporated into these practices, as well as into research and development of new hearing devices. With such methods, device features may be optimized and customized better for individuals, by taking into account more complex mechanisms of speech perception. Similarly, manufacturers may be able to better assess new device features. There is a possibility that some features are currently under-assessed, due to lack of such measures, and are perhaps discarded when they do not show a clear benefit in speech intelligibility. And lastly, new rehabilitation and training programs can be developed that take into account the cognitive processes of speech.

REFERENCES

Baddeley, A.D., & Hitch, G.J. (**1974**). Working memory. The Psychology of Learning and Motivation, Vol 8, 47-89.

Başkent, D. (**2010**). Phonemic restoration in sensorineural hearing loss does not depend on baseline speech perception scores. J Acoust Soc Am, 128, EL169-EL174.

Başkent, D. (**2012**). Effect of speech degradation on top-down repair: Phonemic restoration with simulations of cochlear implants and combined electric–acoustic stimulation. J Assoc Res Otol, 13, 683-692.

Başkent, D., Eiler, C.L., and Edwards, B. (**2010**). Phonemic restoration by hearing-impaired listeners with mild to moderate sensorineural hearing loss. Hear Res, 260, 54-62.

Benard, M.R., Mensink, J.S., and Başkent, D. (**2014**). Individual differences in top-down restoration of interrupted speech: Links to linguistic and cognitive abilities. J Acoust Soc Am, 135, EL88-EL94.

Benard, M.R., and Başkent, D. (**2014**). Perceptual learning of temporally interrupted and spectrally degraded speech. J Acoust Soc Am 136, 1344-1351.

Bergman, M., Blumenfeld, V. G., Cascardo, D., et al. (**1976**). Age-related decrement in hearing for speech: Sampling and longitudinal studies. J Gerontol, 31, 533-538.

Best, C.T., Morrongiello, B., and, Robson, R. (**1981**) Perceptual equivalence of acoustic cues in speech and nonspeech perception. Perception and psychophysics 29, 191-211.

Bhargava, P., Gaudrain, E., and Başkent, D. (**2014**). Top–down restoration of speech in cochlear-implant users. Hear Res, 309, 113-123.

Bhargava, P., Gaudrain, E., and Başkent, D. (**2015**). The intelligibility of interrupted speech: Cochlear implant users and normal hearing listeners. J Assoc Res Otolaryn, accepted with revision.

Blamey, P., Artieres, F., Başkent, D., et al. (**2013**). Factors affecting auditory performance of postlinguistically deaf adults using cochlear implants: An update with 2251 patients. Audiol Neurotol, 18, 36-47.

Chatterjee, M., Peredo, F., Nelson, D., and Başkent, D. (**2010**). Recognition of interrupted sentences under conditions of spectral degradation. J Acoust Soc Am, 127, EL37.

Clarke, J., Başkent, D., and Gaudrain, E. (**2015**). Pitch and spectral resolution: a systematic comparison of bottom-up cues for top-down repair of degraded speech. J Acoust Soc Am. Under revision.

Dahan, D., and Gaskell, G.M. (**2007**). The temporal dynamics of ambiguity resolution: Evidence from spoken-word recognition. J Mem Lang, 57, 483-501.

Friesen, L.M., Shannon, R.V., Başkent, D., and Wang, X. (**2001**). Speech recognition in noise as a function of the number of spectral channels: comparison of acoustic hearing and cochlear implants. J Acoust Soc Am, 110, 1150-1163.

Gillette, M., & Wit, E.-J. C. (**1998**). What is linguistic redundancy: Technical report. (http://www. maths. unsw. edu. au/statistics/preprints/1998/s98-25).

Gordon-Salant, S., & Fitzgibbons, P. J. (**1993**). Temporal factors and speech recognition performance in young and elderly listeners. J Sp Hear Res, 36, 1276-1285.

Hecker, M.H., Stevens, K.N., and Williams, C. E. (1966). Measurements of reaction time in intelligibility tests. J Acoust Soc Am, 39, 1188-1189.

Hornsby, B.W. (**2013)**. The effects of hearing aid use on listening effort and mental fatigue associated with sustained speech processing demands. Ear and Hear 34, 523-534.

Kahneman, D. (**1973**). Attention and effort: Citeseer.

Pichora-Fuller, K.M. (**2008**). Use of supportive context by younger and older adult listeners: Balancing bottom-up and top-down information processing. Int J Audiol, 47, 72-82.

Kawahara, H., and Morise, M. (**2011**) Technical foundations of TANDEM-STRAIGHT, a speech analysis, modification and synthesis framework. SADHANA - Academy Proceedings in Engineering Sciences 36, 713–722.

Koga, Y., and Morant, G. (**1923**). On the degree of association between reaction times in the case of different senses. Biometrika, 15, 346-372.

Lazard, D.S., Innes-Brown, H., and Barone, P. (**2014**). Adaptation of the communicative brain to post-lingual deafness. Evidence from functional imaging. Hear Res, 307, 136-143.

Lippman, R.P. (**1996**). Accurate consonant perception without mid-frequency speech energy. IEEE Trans Speech Audio Process. 4, 66-69.

Mackersie, C. L., & Cones, H. (**2011**). Subjective and psychophysiological indices of listening effort in a competing-talker task. J Am Acad Audiol, 22, 113.

Marslen-Wilson, W.D., and Welsh, A. (**1978**). Processing interactions and lexical access during word recognition in continuous speech. Cog Psychol, 10, 29-63.

Mattys, S.L., Davis, M.H., Bradlow, A.R., and Scott, S. K. (**2012**). Speech recognition in adverse conditions: A review. Lang Cog Proc, 27, 953-978.

McGarrigle, R., Munro, K.J., Dawes, P., et al. (**2014**). Listening effort and fatigue: What exactly are we measuring? A British Society of Audiology Cognition in Hearing Special Interest Group ‘white paper’. Int J Audiol, 53.

Miller, G.A., and Licklider, J.C.R. (**1950**). The intelligibility of interrupted speech. J Acoust Soc Am, 22, 167-173.

Moore B.C.J., Carlyon R.P. (**2005**). Perception of pitch by people with cochlear hearing loss and by cochlear implant users. In: Plack CJ, Oxenham AJ, Fay RR, Popper AN (eds) Pitch: neural coding and perception. Springer, New-York, NY, 234-277.

Nelson, P.B., and Jin, S.H. (**2004**). Factors affecting speech understanding in gated interference: cochlear implant users and normal-hearing listeners. J Acoust Soc Am, 115, 2286-2294.

Pals, C., Sarampalis, A., and Başkent, D. (**2012**). Listening effort with cochlear implant simulations. J Sp Lang Hear Res, 56, 1075-1084

Pals, C., Sarampalis, A., Van Rijn, H., and Başkent, D. (**2015**). Validation of a simple response-time measure of listening effort. J Acoust Soc Am, in press.

Rabbitt, P. M. (**1968**). Channel-capacity, intelligibility and immediate memory. The Quarterly Journal of Experimental Psychology, 20, 241-248.

Rudner, M., Ng, H. N., Rönnberg, N., Mishra, S., Rönnberg, J., Lunner, T., and Stenfelt, S. (**2011**). Cognitive spare capacity as a measure of listening effort. J Hear Sci, 1, 47-49.

Saija, J.D., Akyürek, E.G., Andringa, T.C., and Başkent, D. (**2014**). Perceptual restoration of degraded speech is preserved with advancing age. J Assoc Res Otol, 15, 139-148.

Salthouse, T.A. (**1996**). The processing-speed theory of adult age differences in cognition. Psychol Rev, 103, 403-428.

Salthouse, T.A. (**2004**). What and when of cognitive aging. Curr Dir Psychol Sci, 13, 140-144.

Sarampalis, A., Kalluri, S., Edwards, B., and Hafter, E. (**2009**). Objective measures of listening effort: Effects of background noise and noise reduction. J Sp Lang Hear Res, 52, 1230-1240.

Stickney, G.S., Zeng, F.G., Litovsky, R., and Assmann, P. (**2004**). Cochlear implant speech recognition with speech maskers. J Acoust Soc Am, 116, 1081-1091.

Wagemans, J., Elder, J.H., Kubovy, M., Palmer, S.E., Peterson, M.A., Singh, M., and von der Heydt, R. (**2012**). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figure–ground organization. Psych Bull 138, 6, 1218–1252.

Wagner, A., Pals, C., de Blecourt, C., Sarampalis, A., and Başkent, D. (2015). Does signal degradation affect top-down processing of speech? Proc. International Symposium on Hearing, Groningen, The Netherlands.

Warren, R.M. (**1970**). Perceptual restoration of missing speech sounds. Science, 167, 392-393.

Wingfield, A. (**1975**). Acoustic redundancy and the perception of time-compressed speech. J Sp Lang Hear Res, 18, 96-104.

Winn, M.B., Edwards, J.R., and Litovsky, R.Y. (**2015**). The impact of auditory spectral resolution on listening effort revealed by pupil dilation. Ear Hear, e-pub.

Zekveld, A.A., Kramer, S.E., & Festen, J.M. (**2010**). Pupil response as an indication of effortful listening: The influence of sentence intelligibility. Ear Hear, 31, 480-490.