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Commentary

The Role of Cognition in Age-Related Hearing Loss

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Abstract

The article presents a commentary on the accompanying six papers from the perspective of a cognitive psychologist. Treisman's (1964, 1969) levels of analysis model of selective attention is suggested as a framework within which the interactions between 'bottom-up' auditory factors and 'top-down' cognitive factors may be understood. The complementary roles of auditory and cognitive aspects of hearing are explored, and their mutually compensatory properties discussed. The findings and ideas reported in the six accompanying papers fit well into such a 'levels of processing' framework, which may therefore be proposed as a model for understanding the effects of aging on speech processing and comprehension.

Key Words: Attention, aging, audibility, bottom-up, cognition, compensation, level of processing, memory, top-down

Abbreviations: ERP = event-related potential; ORN = object-related negativity; MMN = mismatch negativity; S/N = signal/noise; UFOV = useful field of view

Sumario

El artículo presenta un comentario sobre los seis trabajos acompañantes desde la perspectiva de un psicólogo de la cognición. Se sugiere el modelo de Treisman (1964, 1969) de niveles de análisis de la atención selectiva como el marco dentro del cuál las interacciones entre los factores de atención "de abajo hacia arriba" y los factores cognitivos de "de arriba hacia abajo" pueden ser comprendidos. Se exploran los papeles complementarios de los aspectos auditivos y cognitivos de la audición y se discuten sus mutuas propiedades compensatorias. Los hallazgos e ideas reportados en los seis trabajos acompañantes calzan bien en dicho marco de "niveles de procesamiento", los que puede, por tanto, ser propuestos como un modelo para comprender el efecto del envejecimiento para el procesamiento y la comprensión del lenguaje.

Palabras Clave: Atención, envejecimiento, audibilidad, de abajo hacia arriba, cognición, compensación, nivel de procesamiento, memoria, de arriba hacia abajo.

Abreviaturas: ERP = potencial relacionado con el evento; ORN = negatividad relacionada con el objeto; MMN = negatividad desigual; S/N = señal/ruido; UFOV = campo útil de visión

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When older adults report hearing difficulties, the obvious reaction is to restore audibility by means of hearing aids of one type or another. This focus on signal properties and sensory processing mechanisms seems well justified in light of the finding (reported by Humes, this issue) that, in older adults, between 65% and 90% of the variance in speech understanding is attributable to losses in high-frequency hearing abilities. Difficulties in comprehension still persist, however, even after audibility has been restored to a reasonable level, and now performance correlates more highly with individual differences in cognitive variables than with differences in hearing loss (Humes, this issue). Such results have led audiologists and researchers working on problems of hearing loss to acknowledge the importance of cognitive factors, and to build them into their models of comprehension. The present six articles reflect this concern.

The role of this commentary is to consider the ideas and findings reported in the preceding articles from the perspective of a cognitive psychologist. The general notion that both sensory and cognitive factors must play some part in acceptable models of word recognition and speech understanding has been prominent in the psychological literature since the 1950s when the cognitive approach became dominant. The idea of a hierarchy of processing stages has been central to models of word recognition and speech comprehension, with early sensory analyses proceeding through levels of feature, grapheme and phoneme identification to levels concerned with analysis of words, sentences and meaning. It has also been widely accepted that information flows both "bottom-up" from sensory to conceptual analyses and also "top-down" in the other direction. The overall process is in fact interactive, with clearly identifiable signals from the environment driving recognition in a bottom-up manner, but interacting with conceptual and contextual factors generated from past experience and recent exposure to the current source (see also Wingfield and Tun, this issue). This general framework can serve not only as an account of how meaning is extracted from the speech signal, but also as a way to understand the processes of attention, working memory, and long-term memory. The following sections spell out some main ideas in this connection, how mechanisms and processes may be affected by aging, and how theories and data might contribute to an understanding of hearing problems in the lab and in the clinic.

LEVELS OF PROCESSING IN ATTENTION AND MEMORY

Early studies of selective attention showed clearly that experimental participants could select one "channel" of information (e.g., a particular talker, one spatial source, visual rather than auditory inputs). It was not surprising to find that when participants were exposed to two simultaneous auditory inputs in the dichotic listening paradigm, they could report very little of the unattended message—they sometimes failed even to detect a switch to another language! (Cherry, 1957; Treisman, 1964, 1969). More interestingly, listeners *did* perceive highly meaningful information from the unattended channel, prompting the question of how meaningful messages get through to consciousness if selective attention acts simply to filter out unattended messages at an early stage. The best solution to this puzzle came from Anne Treisman (1964, 1969) who suggested that attention acts *throughout* a series of levels of analysis, running from early sensory analyses through stages concerned with analysis of phonemes and syllables to stages concerned with identification of words and interpretations of phrases. Treisman hypothesized that each successive stage acts as a test, and that incoming messages either pass the test and proceed to the next higher stage, or fail the test, in which case the message is not analyzed further. Each test has the properties of signal detection theory (Macmillan and Creelman, 1991); thus "passing the test" depends both on signal strength (d') and on the criterion (β) of how much relevant information is acceptable. If a message fails a test early on, aspects of it will nevertheless be perceived in terms of the analyses that have been carried out, so listeners may be able to tell that there is a voice on the unattended channel and that the talker is a woman, but little else. Treisman further suggested that signal strength aspects are set bottom-up by the input, whereas criterion aspects are set top-down in terms of long-term importance (e.g., the listener's own name) or short-term context effects. Thus both loud messages and meaningful messages will get through to conscious awareness even if they are on an unattended channel, but for different reasons.

The implications of this approach for studies of hearing are, first, the obvious point that adequate perception and comprehension depend on both bottom-up auditory factors and top-down cognitive factors; second, that these two sets of factors are reciprocal and mutually compensatory; third, that the system is very flexible and malleable and that improvements of rather different kinds will emerge depending on where attentional processes are allocated (Wingfield and Tun, this issue)—that is, whether they are allocated to tuning the system to be more sensitive to certain frequency bands or spatial directions on the one hand, or allocated to elaborating and enriching the semantic context on the other. This account fits well with the description of cognitive supports and constraints in the article by Wingfield and Tun (this issue). Two small differences in emphasis are, first, that whereas they say that their review deals with cognitive and linguistic systems operating once the input "has been registered and encoded by the nervous system," my reading of Treisman's model is that "registration" and "encoding" are not categorical events but rather reflect graduated degrees of processing along the sensory-conceptual continuum. Attention and perception do not occur *after* registration and encoding but are constituent aspects of such encoding processes. The second point is that, in my view, the ready perception of highly meaningful information such as a person's name does not occur "by occasionally sampling from a short-lasting attenuated trace" but rather because meaningful information benefits from the lenient criterion settings of the "tests" associated with successive stages of processing. Generally, however, I find their account very congenial, although I think that we are all a bit vague about what "processing resources" really are!

The notion of attentional resources applies to the concept of working memory as well as to the processes of perception and comprehension. As described by Wingfield and Tun, working memory is a mechanism (or set of processes) that enables the listener to hold part of an utterance temporarily while processing its meaning or while waiting for the rest of the sentence to be spoken. Information "in working memory" is in conscious awareness, and this stage of processing is crucial to the comprehension of speech and language. It is usually thought of as a relatively peripheral device, but the fact that the number of words that can be recalled immediately (memory span) is only 5–6 for unrelated words but 20 or more for words in a sentence, makes that quite unlikely. One solution is that the term "working memory" should refer to a *family* of "computation spaces," each working as the computational aspect of a specific domain of knowledge. This idea stands in contrast to the more usual notion of one central working memory that deals with various types of information (e.g., Baddeley and Hitch, 1974). Caplan and Waters (1999) have suggested a dedicated working memory system for syntactic processing, but there may be different working memory abilities for a *variety* of domains—e.g., music, chess, number, phonology etc.—with the "capacity" of each system depending on the person's expertise in that domain. A similar position was advanced by Daneman and Tardif (1987); they found that reading ability was well predicted by performance on a verbal working memory task, less well predicted by mathematical span, and not at all predicted by spatial span. One implication here for the clinical assessment of hearing disorders is that cognitive tests should reflect the same domain as the target ability (typically speech). The Daneman and Tardif result suggests strongly that there is little point in assessing a patient's "short-term memory" by means of a visuo-spatial span task, if the reason for the assessment is to understand the person's difficulty in understanding spoken speech. The finding reported by Foo et al (this issue) that reading span (for words) was effective in predicting settings for hearing aids but a letter monitoring task was less effective is in good agreement with this point of view.

The Foo et al. (this issue) article also makes the point that highly skilled listeners appear to have "highly capacious explicit working memory functions." My argument is that such listeners essentially have high *verbal expertise*, and that their superior qualities of verbal representation and control are what results in the "expansion" of working memory capacity—in very much the same way that word span may be 6 but sentence span 20 in the same person. In both cases the ability to draw on more elaborated and meaningful structures and processes is reflected in higher performance on such tasks as reading span (Daneman and Carpenter, 1980). In terms of the Treisman model, greater verbal expertise would also have the effect (through relevant knowledge and contextual predictability) of lowering relevant criteria during the analytic process, thereby enhancing the ability of skilled listeners to "better utilize the temporal dips in the noise to uncover the signal" (Foo et al., this issue, p. 620). The notion that skilled listeners are better at recruiting explicit processing strategies to aid comprehension (Foo et al., this issue) also fits well with the idea that verbal expertise comprises aspects of control as well as representation. In studies of memory retrieval, Jacoby (1991) and his colleagues have distinguished between processes giving rise to feelings of general familiarity and those involving explicit conscious recollection; it would be interesting to see if people who have high recollection estimates using Jacoby's procedure are also people who do better on tests of listening in noise.

One final advantage of thinking about attention as a hierarchy of analyzers is that long-term memory encoding may be brought into the same system. Craik and Lockhart (1972) suggested that memory encoding is nothing more than the products of analyses carried out primarily for the purposes of perception and comprehension, and that higher ("deeper") levels of analysis concerned with concepts and meanings result in longer-lasting memory traces. Hearing impairments are relevant here too; as pointed out by Wingfield and Tun (this issue), problems with early sensory analyses will lead to more attentional resources being deployed to these levels, with correspondingly fewer resources remaining to carry out adequate processing at the level of meaning. By the "level of processing" approach this attenuated processing should result in poorer memory for the material in question, and this result has been reported by Rabbitt (1991) and others. Thus deafness can lead to memory problems which could actually be overcome by taking more time to dwell on the meaning of messages once they have been heard and understood.

EFFECTS OF AGING ON ATTENTION AND INFORMATION PROCESSING

Given the importance of cognitive processes to an understanding of hearing, it follows that age-related impairments in cognition will have profound effects on the older person's ability to hear and comprehend speech. That is, repairing audibility by means of hearing aids is only part of the story; it is also important to understand the cognitive problems of older adults, with a view to reducing them wherever possible. Unfortunately, however, "cognitive aids" are less easy to devise and manufacture than aids that boost audibility, so efforts to reduce cognitive problems in older listeners are largely a matter of ensuring that both the external environment and the listener's internal cognitive environment are set optimally to perceive, understand, and act on current communications.

In order to achieve these goals, it is necessary to have some knowledge of age-related changes in the cognitive system, and it seems very likely that there are many different changes although typically researchers tend to champion their own favorite theory. There is no doubt that mental processes slow down as a function of aging, and it is likely that such slowing is more pronounced at higher levels of thought and decision (Welford, 1958). This age-related slowing has negative effects on cognitive processing (Salthouse, 1991, 1996), but it is important to note that full cognitive powers would not be restored simply by giving older adults more time to complete cognitive operations. Salthouse (1996) has suggested that complex processes require temporal coordination and that if some components are delayed, the cognitive act (like a skilled motor act) will become clumsy and inefficient. Working memory processes also become less effective, partly for the same reasons and partly because inhibitory processes are less efficient with increasing age, leaving working memory "cluttered" with unwanted material (Hasher and Zacks, 1988; Zacks et al, 2000). Finally, Craik and Byrd (1982) proposed that processing resources decline with age, so that cognitive operations lack the "mental energy" to run them off efficiently.

These various changes in the underlying biology, plus strategic changes such as the age-related differences in self-efficacy described by Wingfield and Tun (this issue), result in changes at the cognitive level that affect the older person's ability to hear and comprehend. Attentional processes are less efficient, so that older adults are less able to select a wanted channel (Kramer and Madden, 2007; McDowd and Shaw, 2000) and have greater difficulty segregating wanted signals from unwanted signals and background noise (Kramer and Madden, 2007).

This difficulty also makes them more vulnerable to interference and therefore more distractable; the ability to focus and "concentrate" is weaker than in their younger counterparts (McDowd and Shaw, 2000). Switching from one mental focus to another takes longer (Meiran and Gotler, 2001). When attention must be divided between two sources older people are more penalized, perhaps because division of attention requires executive management that is more resource-consuming than in younger adults (Craik et al, 1996; Kramer and Madden, 2007). Working memory processes are less effective, as mentioned above, with consequent problems in both memory encoding and memory retrieval (Craik and Jennings, 2000; Zacks et al., 2000). In general, higher order cognitive processes appear to be more affected by aging than are early sensory processes. Thus, abilities such as making inferences (Zacks and Hasher, 1988), associative connections and binding (Chalfonte and Johnson, 1996; Naveh-Benjamin, 2001) typically show age-related losses. This last point is in good agreement with the observations of Lunner and Sunderwall-Thorén (this issue) and of Foo et al. (this issue) that listening performance in complex conditions correlates with performance on cognitive tests rather than with simple tests of audibility.

If these are the cognitive problems of aging, what can be done to remedy the situation? One obvious set of factors relates to the external environment; comprehension will be better to the extent that the listener's surroundings are quiet and free of distracting stimuli. Somewhat less obviously, comprehension will also improve to the extent that the environment supports the activation of relevant cognitive schemas; that is, optimally the environment should help to reinstate the mental context appropriate to the topic under discussion. Theoretically at least (I don't know of any relevant studies) interviews about problems relating to family and home circumstances should yield more useful information when held in the patient's home than in a doctor's office. The activation of appropriate semantic and linguistic contexts is also crucial when considering the internal mental environment. As discussed by Wingfield and Tun (this issue), and also at greater length by Wingfield and Stine-Morrow (2000), the provision of various aspects of cognitive context is particularly helpful to the older listener. These aspects range from appropriate prosody through ability to predict the next words from local context ("the boy leaned out the ______ ?") to learned knowledge of syntax and "world knowledge" relevant to the current topic (Wingfield and Stine-Morrow, 2000). Even under optimal conditions the older listener may have to devote considerable attentional effort to perception and comprehension, as Wingfield and Tun point out. They also emphasize the useful distinction between data-limited and resource-limited hearing difficulties (Norman and Bobrow, 1975); that is, conditions under which hearing can be improved only by improving signal quality or the S/N ratio ("data-limited") as opposed to conditions under which the allocation of more attentional resources will boost relevant cognitive processing ("resource-limited"). In terms of the hierarchical model, listening and comprehension may be improved either (or both) by means of interventions at early sensory stages or later cognitive stages of processing, and such interventions will provide improvements that are complementary when considering the overall picture.

DISCRIMINATION, MASKING AND COMPENSATION

The article by Alain and Tremblay (this issue) explicitly endorses the levels of analysis model suggested by Treisman (1964) and others, and their paper discusses ways in which analyses at early and late processing levels may interact. Their use of ERPs is particularly relevant in this respect, as the precise time measurement enables researchers to explore both quantitative and qualitative differences associated with successive levels of processing. It makes good sense that the early P_1-N_1-P_2 complex is sensitive to such factors as the duration and intensity of incoming signals, but is *not* sensitive to attentional manipulations (Alain and Kelly, 2007); as the authors remark, analyses of such low levels of scene analysis are carried out automatically. This complex is thus useful clinically to assess the "physiological" transmission of the encoded signal to the cortex, but not to assess processing of more cognitive aspects. Mismatch negativity (MMN) appears more promising in this latter respect, although the fact that perception of mistuned harmonics corresponds to a wave that peaks at only 150 ms after sound onset, and the fact that the wave is minimally affected by attention (Alain and Tremblay, this issue) suggests that this form of negativity also reflects quite early stages of signal processing. Even the double vowel task described by Alain and Tremblay appears to tap early analytic processes given that its associated object-related negativity (ORN) again peaks at 150 ms and is again independent of attention. The later N2b wave at 250 ms seems a more promising candidate as a measure of cognitive involvement. In general, it may be possible to cross the general idea of mismatch negativity with the notion of levels of analysis—that is, the stimuli providing the mismatch could range from tones varying in pitch or loudness to speech sounds and words differing in their phonological, phonemic or semantic characteristics. Presumably mismatches at these different levels of analysis would generate mismatch-related activity in different areas of the cortex (see Näätänen and Tiitinen, 1998), and possibly at different latencies. Once developed and refined, such a technique could be very useful clinically to diagnose age-related and other problems in speech perception (see also Alain and Tremblay, this issue; Näätänen and Tiitinen, 1998)

The concept of discrimination is also relevant to issues of masking discussed by Schneider et al (this issue). Their distinction between energetic and informational masking can also be viewed in terms of a processing hierarchy, with energetic masking applying to earlier levels of auditory analysis and informational masking applying to later cognitive analyses. Schneider and colleagues present a useful discussion of the ability to segregate one source of information and the factors, such as age of the listener, that reduce the efficiency of this ability. They suggest that working memory plays a crucial role in the inhibition of unwanted information, but it seems to me that the ability to "tune" the system to segregate information from one talker say, takes place relatively early in the processing hierarchy. In terms of the Treisman model, successful segregation would be a matter of setting the criteria leniently for physical characteristics of the wanted voice while setting the criteria relevant to other voices at a higher, more conservative level. "Maintaining concentration" is then a question of maintaining that configuration of criteria settings; it is helped to the extent that characteristics of competing "channels" differ in various ways (voice frequencies, spatial separation, etc.), and is also helped by cognitive factors working top-down—familiarity with the wanted voice is one major factor and knowledge of the topic is another (Schneider et al, this issue). How this all works is still largely unknown, but Schneider and colleagues present some useful ideas and data that address these complex issues.

One theme that runs through the papers in this collection is the notion that bottom-up and top-down processing act in a complementary manner. The reliance on top-down knowledge of the speaker's voice, knowledge of the spatial location of wanted messages, and knowledge of the topic appears to be greater in older than in younger adults, so these factors should be "primed" as much as possible to maximize the competence of the older listener. The downside of such age-related compensation is that the older listener may rely too much on built-in habits, and so be rather inflexible when the information is novel or unexpected. In general, the more "environmental support" (Craik, 1983) and "contextual support" (Wingfield and Stine-Morrow, 2000) there is, the more older adults will function like their younger counterparts.

One interesting example of audibility/cognitive interactions comes from studies of second language learning and bilingualism. An experiment by Rogers et al (2006) measured word recognition in quiet, noise, and noise with reverberation for monolingual American English speakers and Spanish-English bilinguals who had been exposed to Spanish from birth and exposed to English in early childhood (before age six years). Even although the bilinguals were judged to have no foreign accent in English and spoke English as well as or better than Spanish, they nonetheless identified words less well than their monolingual peers in both types of noise. This result has obvious clinical implications; clinicians should ascertain whether English is the patient's first language and make allowances if it is not. The participants in the Rogers et al. (2006) study were all young adults (aged 25 years on average), so it is at least possible that the slight word identification deficits found in that study would be magnified in older adults. It has been shown in other studies that even fluent bilinguals have smaller vocabularies than monolinguals (Bialystok and Craik, 2007); it is therefore of interest to determine the relations among bilingualism, vocabulary size and speech-in-noise performance, especially bearing in mind the substantial (and growing) proportion of North Americans who speak a language other than English at home.

The other way to look at the preceding result is that bilinguals require a stronger signal (or at least a higher S/N ratio) than monolinguals to recognize and comprehend speech at the same level. That is, higher signal strength will compensate for somewhat less efficient language representation. At the anecdotal level I know that when I listen to French (a language I understand imperfectly) on the radio, I inevitably turn up the volume to boost my comprehension. Just as cognitive factors become progressively more important for adequate hearing under difficult listening conditions (Humes, this issue; Foo et al., this issue; Lunner and Sundewall-Thorén, this issue), so audibility is more critical when cognitive abilities are less than perfect. One set of factors can compensate for deficiencies in the other. Normally these bottom-up and top-down processes are in good dynamic balance, with more attentional effort allocated to signal processing if the material is difficult or the context unpredictable (Pichora-Fuller et al, 1995), and more effort allocated to cognitive processing when the speech signal is faint or noisy (Wingfield and Tun, this issue).

SUMMARY AND IMPLICATIONS

In this commentary I have stressed the hierarchical nature of speech recognition processes, running from the relatively automatic early stages of signal processing to the later attention-demanding cognitive stages. I have also endorsed the point made by many of the accompanying articles that top-down cognitive processes interact with bottom-up analyses that determine audibility to yield the final perceived product. This consciously perceived product obviously includes many sensory qualities (pitch, timbre, prosody) as well as the cognitive aspects of word identification and the construction of meaning. One key element in successful listening is attentional *selection*, and a useful analysis of this process has recently been provided by Enns and Trick (2006). They proposed that selective attention may be classified in terms of two dimensions: automatic-controlled and exogenous-endogenous. They use the latter terms to contrast selection driven by unlearned external stimuli to selection in terms of learned expectations, long-term goals and short-term variations in local context. The Enns and Trick framework generates a 2 x 2 classification in which automatic-endogenous is labeled "Reflex," automatic-endogenous is termed "Habit," controlled-exogenous is labeled "Exploration," and controlled-endogenous is termed "Deliberation." In the context of speech processing, early analyses fall into the "reflex" category with later analyses involving "habit" and "deliberation" depending on whether the communication deals with expected routine matters or with novel unexpected events. Deliberation requires more effortful conscious control than habit, and the availability of such attentional control processes declines with age (Wingfield and Tun, this issue; Craik and Bialystok, 2007). This analysis thus again emphasizes the need to compensate the older listener by providing more time, more contextual support and more support from enhanced signal qualities.

A further point of emphasis is that attention, perception, comprehension, memory and thinking are all aspects of the same cognitive system and that, as such, deficiencies in one aspect will have immediate consequences for other aspects. One example mentioned previously is memory. Good long-term memory depends on the richness and organization of achieved meaning (Craik and Lockhart, 1972); it therefore follows that if processing resources are expended on early analyses of the speech signal, later cognitive analyses will not be performed adequately, the degree of comprehension will suffer, and poorer memory will result. It seems likely that the quality of thinking and decision-making will also suffer under difficult listening conditions. From the practical point of view, it is therefore important to realize that improvements in hearing in older listeners will also result in improvements in memory and decision-making.

A further practical question concerns the possibility of remedial training of attentional processes in older adults. This type of rehabilitation is typically laborious and not very effective, but some recent studies suggest that the further development of relevant techniques may be very worthwhile. In the area of driving behavior, Ball and colleagues have shown first that the "useful field of view" (UFOV) is restricted in older adults, but that this aspect of visual attention can be improved by as much as 133% after only 5 days of training (Ball et al, 1988). Most dramatically, these improvements were maintained for six months without further training. It seems probable that UFOV reflects cognitive/attentional factors as well as purely visual factors (McDowd and Shaw, 2000), although it is unclear which aspects are enhanced by training. Other prolonged experiences such as bilingualism (Bialystok et al, 2004) and playing video games (Green and Bavelier, 2006; Castel et al, 2005) also improve aspects of visual attentional control in younger and older adults. Similar work in the domain of hearing would be important and timely.

A final practical concern is the nature of tests that can usefully assess the older listener's cognitive abilities. The important point here is that "cognition" is not one monolithic entity, and that tests of one cognitive function may have little bearing on another. This point is illustrated in the area of reading by the finding that whereas a measure of verbal working memory correlated highly with reading comprehension, a measure of numerical working memory correlated much less, and a measure of spatial working memory did not predict comprehension at all (Daneman and Tardif, 1987). The message is therefore that assessments of cognitive processing in the context of speech perception should similarly involve "transfer-appropriate" cognitive functions, presumably again verbal in nature. Vocabulary level may be one straightforward indicator; tests with proven reliability and validity include the reading span test of working memory (Daneman and Carpenter, 1980) and the SPIN test (Pichora-Fuller et al., 1995). Finally, a quick test that may be useful clinically is "alpha span" (Craik, 1986) in which participants are given short lists of words and must rearrange them mentally into alphabetical order before responding.

In conclusion, the preceding papers show that audiologists and speech researchers are now very aware of the important role of cognitive factors in speech processing and in deaf listeners. Audibility and cognitive components are interactive and mutually compensatory. Further efforts should now go into developing models that embrace both aspects of the overall speech recognition process; the payoff will be a better understanding of hearing and listening in the laboratory, and more effective methods of assessment and treatment in the clinic.

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