How Our Brains Make Sense of Noisy Speech

Jonathan E. Peelle and Arthur Wingfield

Introduction

In August 1909, the French otolaryngologist Étiene Lombard came before a meeting of the French Academy of Sciences to report on the phenomenon that now bears his name. In the presence of a noisy background, speakers automatically talk louder in an attempt to maintain an effective signal-to-noise ratio (that is, keep their speech louder than the background noise so it can be heard) (Lombard, 1911). As anyone who has had a meal in a small noisy restaurant or a loud social gathering knows, the "Lombard effect" can quickly escalate, with all of the others in the room similarly attempting to speak louder than the other speakers. A surreptitious glance at your cell phone-based sound level meter can reveal startling levels of background babble.

Fortunately, when dealing with noise, whether in a restaurant or another potentially loud environment, the mammalian auditory system has evolved ways to extract a signal of importance (a partner's speech!) from the noisy surround. Although many of the mechanisms lie within the ear itself (Litovsky, 2012), the brain has also evolved amazing ways to enhance speech comprehension in the presence of noise. The focus of this article is the effects of noise on speech comprehension and the neural systems engaged when a listener is faced with this challenge.

During spoken communication, listeners need to determine the words produced by a talker so that they can understand the intended meaning. For many people, understanding speech in relaxed settings feels relatively automatic and effortless. However, this feeling is at odds with the remarkably complex feat our auditory system performs, namely, mapping a rapid and acoustically complex stimulus onto a set of learned categories (words). The average university graduate has a speaking vocabulary of tens of thousands of words and an even larger comprehension vocabulary. The listener's task, then, is to match the incoming acoustic input with the relevant mental representations (the "mental lexicon") of the words they know. What may be even more impressive is that this process must occur as the information is arriving at average speech rates of 140 to 180 words per minute, passing the ear, literally, at the speed of sound. Thus, much of our analysis of the speech signal lags behind the arriving acoustic input and must be carried out on a fading trace of the input in our short-term memory.

Given the time constraints governing speech perception, listeners become experts at using knowledge about speech and language, including what words are likely to come next given the preceding context, to aid understanding. So, for example, if you hear the sentence "I like cream and sugar in my…" you might expect the next word to be "coffee" or perhaps "tea," and this expectation will aid your understanding (coffee and tea will be recognized more quickly and accurately than "toffee"). Or, when listening to an unfamiliar talker, listeners typically adjust to this talker over time and become more efficient at understanding their speech. Even though the incorporation of acoustic and linguistic expectations usually happens without a listener's conscious awareness, on some level their brain is rapidly processing these types of information.

Although listening in quiet may feel relatively easy, listening in background noise can be noticeably challenging. Even when background noise does not completely drown out a talker, it can obscure sounds and make words ambiguous or unintelligible. And, if the background noise consists of other speech (as frequently happens in a coffee shop or restaurant), the content of the background speech can also be distracting (especially if it's interesting!). It is no wonder that listening to speech in

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noise is a chief complaint among people seeking hearing health care.

Despite the challenges that background noise presents for speech perception, in many cases listeners are nevertheless able to correctly understand what a talker has said. Here, we explore the ways that listeners' neural systems within the brain deal with speech that is acoustically challenging. We use the term "acoustically challenging" speech to cover a broad range of challenges such as speech in background noise, speech heard in the midst of other talkers, understanding speech by listeners with hearing loss, and understanding the spectrally degraded sound delivered by a cochlear implant. We focus on studies suggesting that our brains need to "work harder" when listening to acoustically challenging speech than they do when listening to acoustically clear speech and the implications these findings have for everyday communication.

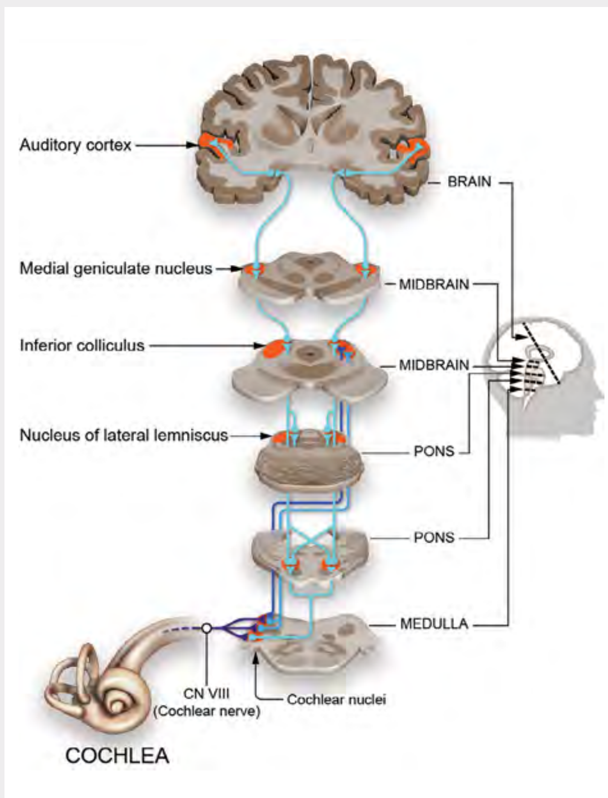
The Brain Systems Involved in Understanding Speech

Before exploring how listeners' brains respond to *challenging* speech, it will be helpful to review the core brain regions involved in understanding both sounds and speech. This pathway from the ears to the cortex is shown in **Figure 1**. Auditory information is passed from the cochlea (the inner ear) to the auditory nerve and then along several auditory nuclei (a nucleus is a collection of cells with similar function). These nuclei function, in part, to compare signals from the left and right ears to extract cues to spatial location, which can also aid in disentangling a target sound from background noise. Auditory information reaches the cortex in Heschl's gyrus (primary auditory cortex) on the top portion of the temporal lobe. From here, different brain regions are engaged depending on what is being heard (e.g., simple tones, speech, or environmental sounds) and the task being done.

In a side view, the four lobes of the brain (frontal, temporal, occipital, and parietal) are shown in the left hemisphere (**Figure 2a**). Investigators first learned about the brain regions involved in speech by observing patients who have had brain damage (e.g., due to a stroke) and who have, as a result, developed language difficulty (known as *aphasia*). The two most widely known types of aphasia are Broca's aphasia (caused by damage to the left frontal lobe and associated primarily with difficulty producing speech) and Wernicke's aphasia (caused by damage to the left temporal lobe and associated primarily with difficulty comprehending speech). These conditions early on pointed toward an important role for the left hemisphere in understanding speech as well as highlighting contributions from both the temporal and frontal regions.

However, a great deal has been also learned from functional brain-imaging studies in which we are able to measure regional brain activity while people listen to speech. Among imaging approaches, functional magnetic resonance imaging (fMRI) has long been the most popular due to its wide availability (nearly every hospital or medical center has an MRI scanner) and spatial precision (Evans and McGettigan, 2017). fMRI takes

Figure 1. *Auditory processing pathways.* ***Left:*** *each region shown is a cross section of the brain at a different level of the auditory system.* ***Right:*** *side view of the brain. Sound enters the auditory system in the cochlea (inner ear) before proceeding up a complicated set of subcortical nuclei leading to the primary auditory cortex. Available at osf.io/u2gxc, under CC BY 4.0 Attribution 4.0 International license. See also Peelle and Wingfield (2016).*



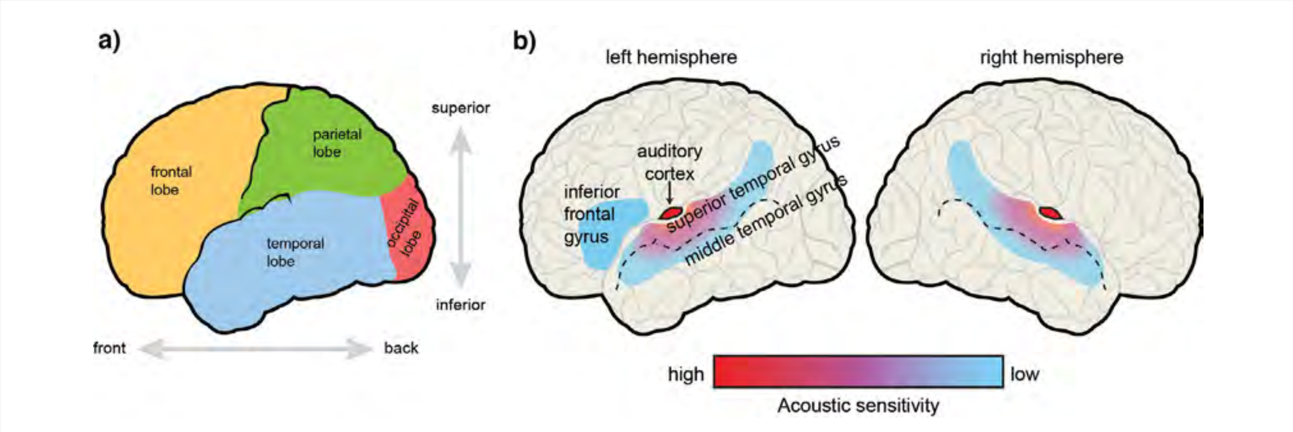


Figure 2. ***a:*** *Side view (also known as a lateral view) of the left hemisphere, with the four lobes of the brain indicated. Superior is used for structures closer to the top of a lobe or structure and inferior for those closer to the bottom.* ***b:*** *Views of the left and right hemispheres showing the cortical speech regions. From the auditory cortex, parallel pathways process speech with an increasing abstraction, reflecting increasingly less acoustic detail. Adapted from Peelle et al. (2010).*

advantage of the fact that areas of the brain increasing their relative level of activity draw an increase in the relative blood flow to that area to bring the oxygen needed to sustain this activity. The blood carrying oxygen (oxygenated hemoglobin) has different magnetic properties than deoxygenated hemoglobin, which can be detected by an MRI scanner.

Thus, although historically the language difficulties of people who lost functions due to brain damage gave us the broad outlines of regions in the left hemisphere important for language, fMRI and other modern brain-imagining techniques provided a more nuanced and complete view of core speech-processing regions (summarized in **Figure 2b**). What this modern work has shown is that when listening to single words, both the left and right temporal lobes are engaged. This includes not only the primary auditory cortex but also nearby regions on the superior temporal gyrus and middle temporal gyrus. (The surface of the human brain is not smooth but folded. A *gyrus* is a bump or a "mountain," and a *sulcus* is the crevice between bumps or a "valley.") Together, these regions of the left and right temporal lobes, encompassing the auditory cortex, superior temporal gyrus, and middle temporal gyrus, are responsible not only for processing the acoustic information in speech but also for linking the acoustic information to words and word meaning.

When listening to sentences and stories, the left inferior frontal gyrus also becomes active. Although the specific contribution of this frontal activity is debated (complicated by many smaller subdivisions of the inferior frontal cortex that seem to play distinct roles), many of these functions appear to relate to the rules for combining words to form a meaningful sentence. These grammatical rules are referred to as the syntax of a sentence. Regions of the left inferior frontal gyrus also respond to more complicated aspects of word meaning, such as understanding from the context whether "bark" might refer to the sound a dog makes or the covering on a tree. Thus, the core regions supporting speech understanding start with the auditory cortex and then continue to a more extended network concerned with various levels of language processing.

A key characteristic of human speech regions is that they are hierarchically organized; stages anatomically nearer the auditory cortex are more involved in processing the specific acoustic signatures of speech. For example, they respond differently depending on how speech is degraded (different kinds of background noise result in different patterns of brain activity). By contrast, activity in regions that are further away, such as in the frontal lobe, depends less on the acoustic details of speech and more on the informational content (e.g., whether speech is intelligible). These different components of the speech network work in a coordinated way to translate the acoustic speech signal to its intended meaning.

How Young Adults with Normal Hearing Make Sense of Degraded Speech

Even young adults with good hearing must make sense of noisy speech. One way to study the cognitive consequences of noisy listening is through behavioral measures, such as asking people how well they remember what they have heard. Memory studies are useful for two reasons. First, in everyday life, we often would like to remember what we hear, and so studying the effect of acoustic challenge on memory has clear real-world implications.

Second, there is a clear theoretical framework that lets us use memory differences to understand cognitive processing. Specifically, such studies rely on the principle that the brain is limited in its computing capacity. Thus, if people are worse remembering noisy speech compared with easy-to-understand speech, it suggests that the presence of background noise increased cognitive demand during listening.

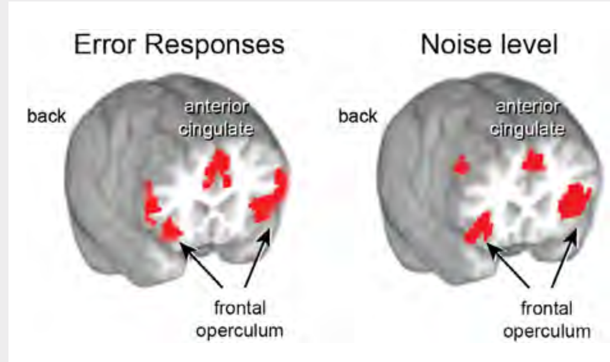


Figure 3. *Two images of a brain with a cross section cut to show deep structures (the very front of the brain has been removed).* ***Red****, regions of brain activity associated with error responses (*__*left*__*) and noise level (*__*right*__*). For young adults with normal hearing, the cingulo-opercular network composed of the anterior cingulate and bilateral frontal operculum is engaged during difficult listening, for both error responses and elevated noise conditions. These regions are not typically associated with speech processing in easy-listening situations. Adapted from Vaden et al. (2013).*

Of course, it is not very interesting to find that people have trouble "remembering" something if it was never understood in the first place. Thus, the clearest demonstrations of the effect of noise on memory occur when speech in noise is shown to be audible in an intelligibility check. In an early demonstration of this effect, Rabbitt (1968) presented listeners with lists of digits to recall. In one condition of his experiment, the second half of the list was always presented in clear, unprocessed, easy-to-understand speech. The first half of the list was sometimes presented in clear speech and at other times acoustically degraded speech. In this latter case, Rabbitt made sure that the words could still be understood (although with effort). Rabbitt found that when the first half of the list was degraded, listeners had trouble remembering the second half of the list. Acoustically, there is no reason for this change; the speech in the second half of the list was always clear and easy to understand. Rabbitt concluded that additional cognitive resources were required for the degraded speech to be understood, such that fewer resources were available for remembering subsequent information. Since this landmark demonstration, many other studies have shown that acoustic challenge interferes with memory, even when speech is intelligible (for a review, see Peelle, 2018).

These behavioral studies linking acoustic challenge and memory suggest that a cognitive resource is used for both types of processing, and therefore increasing the cognitive demands of listening "steals" cognitive resources away from memory. Functional brain-imaging studies investigating how listeners process degraded speech are broadly consistent with this hypothesis, identifying regions of the frontal lobe not typically seen during "easy" speech perception that become more active when speech is acoustically challenging. In an elegant demonstration of this effect, Vaden and colleagues (2013) presented single words in background noise to listeners and had them repeat back each word as a measure of accuracy. The noise was difficult enough that some of the words were repeated correctly, whereas others were not. The results are shown in **Figure 3**, which includes two pictures of the brain highlighting different analyses. Following error trials, listeners showed increased activity in a network consisting of the anterior cingulate and frontal operculum, often called the cingulo-opercular network (**Figure 3**, *left*). **Figure 3**, *right*, shows many of the same regions but as a function of the noise levels of the speech. Activity in the cingulo-opercular network is associated with general task engagement and is frequently observed following errors on many kinds of tasks. A particularly compelling aspect of Vaden and colleagues' study is that they found error-related activity in one trial predicted listening success in the *following* trial, consistent with activity in the cingulo-opercular network relating to task reengagement following a mistake.

The cingulo-opercular network is by no means the only brain response to challenging speech in normal-hearing young adults. However, the cingulo-opercular activity is notable for at least two reasons. First, anatomically, it unquestionably lies outside of the core speech network outlined above; the brain is clearly doing something different for degraded speech than it does for easy-to-understand speech. Second, the regions and response profile are consistent with domain-general processing that also goes along with behavioral observations. Understanding speech in noise requires cognitive resources not seen during easy-listening conditions.

Challenges to Speech Understanding in Adult Aging

Among older adults, hearing loss is one of the most common chronic medical conditions (Lethbridge-Cejku et al., 2004). Although age-related hearing loss is primarily a result of cochlear hair cell loss, especially those sensitive to high-frequency sounds, there can also be deterioration throughout the central auditory pathway, from the cochlear nucleus to the auditory cortex (Peelle and Wingfield, 2016). Adult aging is also accompanied by brain changes that affect the structure and network dynamics that carry cognitive function (Peelle and Wingfield, 2016; Anderson et al., 2018). Important consequences of these latter changes include a reduced capacity of working memory, a reduced ability to inhibit potential interference from concurrent stimuli, and a general slowing in a number of perceptual and mental operations. Despite these changes, barring neuropathology, speech comprehension generally remains well preserved in adult aging due in large part to older adults' effective use of linguistic and situational context.

There are, however, several circumstances that present a special challenge for the older listener. These include very rapid speech that places a demand on a slowed processing system, speech in which the meaning is expressed with complex syntax that places a heavy burden on working memory and, relevant to our present topic, speech heard in a noisy background. It is almost axiomatic that older adults have special difficulties in hearing speech in noise, often to a degree that would not be predicted from either auditory sensitivity (e.g., pure-tone thresholds) or the ability to hear speech in quiet (Anderson et al., 2018).

An underlying factor is older adults' reduced effectiveness in perceptually separating the target speech from background noise. This process is sometimes referred to as *auditory stream segregation* (Carlyon, 2004). Many consider these sound streams as "objects" that, once identified, can be selectively attended to (or ignored). Segregating auditory streams depends in large part on spatial cues but also on the physical features of the sounds. In everyday listening, background noise often fluctuates in intensity (amplitude "dips") or periods of brief silence ("gaps"), with there being a benefit to listeners when such dips or gaps are more frequent and of a longer duration. Older adults' speech recognition gains relatively less benefit from gaps and dips in the noise than those in young adults, although this is mitigated to some extent by the effective use of linguistic context.

As hinted, a special case arises when the "noise" consists of other speakers. The term "cocktail party problem" was coined by Cherry (1953) to refer to one's ability to attend to a single speaker while being unaware of the content of other talkers speaking simultaneously (see also Middlebrooks et al., 2017; Leibold et al., 2019). Following a single speaker in a cocktail party situation is more difficult for older adults than for young adults, and especially so for adults with even mild hearing loss. At least part of this decrement is due to interference at the cognitive level (e.g., due to distracting information). In one demonstration of this, we compared younger and older adults on their ability to repeat speech from a target speaker when overlaid by a second talker speaking meaningful English or a language unfamiliar to the listeners (Dutch). Consistent with long-standing findings, the young adults' performance was equally unaffected whether the concurrent speech was in English or Dutch. By contrast, however, when the competing speaker was speaking in meaningful English, the older adults had more difficulty, indicating that the content in the to-be-ignored speech could not be fully ignored (Tun et al., 2002). The fact that the interference was specific to the content of the noise is consistent with the importance of cognitive factors in the comprehension of speech in noise in older adults.

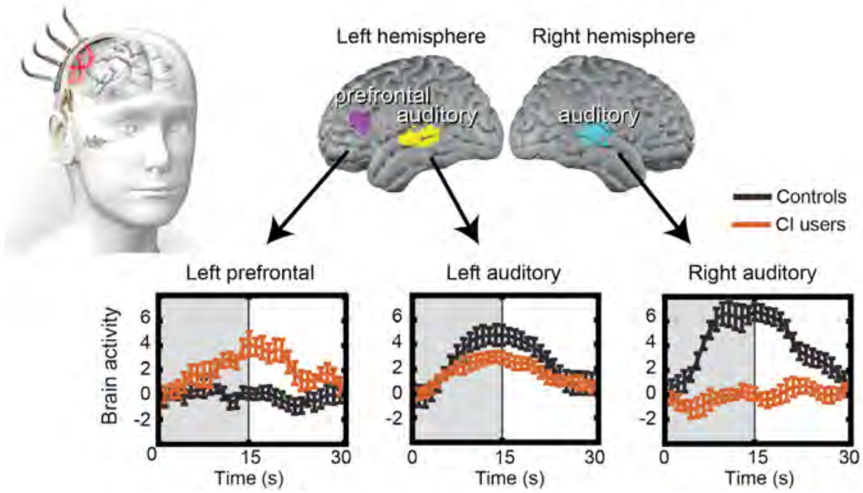


Figure 4. *Optical brain imaging provides a measure of regional brain activity like that obtained from functional magnetic resonance imaging (fMRI). Optical brain imaging was used to look at brain activity in listeners with cochlear implants (CIs) while they listened to spoken words. Three regions were looked at specifically: left auditory cortex, right auditory cortex, and left prefrontal cortex. Listeners with CIs showed different patterns of activity compared with listeners with good hearing, most notably increased activity in the prefrontal cortex. Adapted from Sherafati et al. (2022). Functional near-infrared spectroscopy (fNIRS) figure (**top left**) available at osf.io/t8bxe, under CC BY 4.0 Attribution 4.0 International license.*

Challenges to Speech Understanding from Cochlear Implants

In some cases of deafness, a cochlear implant can be used to restore hearing by electrically stimulating the auditory nerve (Goupell, 2015; Wilson, 2019). The clarity of speech processed through a cochlear implant, however, is sharply degraded compared with what the brain receives from normal (acoustic) hearing. As a result, listeners with cochlear implants frequently find speech understanding very effortful.

One way to measure the cognitive challenge experienced by listeners with cochlear implants is to measure brain activity during listening. However, the cochlear implant hardware presents specific challenges. In particular, patients with cochlear implants typically can't have an MRI, and the hardware also creates electrical and magnetic signals that interfere with other forms of brain imaging. One solution to these challenges has been to use optical brain imaging, commonly referred to as functional near-infrared spectroscopy (fNIRS). In fNIRS, experimenters shine a light on the skull. Some of the light gets absorbed and some travels through the head, into the brain, and back to the surface, where it can be measured. With knowledge about the light wavelengths that are absorbed by oxygenated and deoxygenated hemoglobin, researchers can estimate regional blood flow in the brain that is strongly correlated with brain activity. Optical brain-imaging arrays vary in the number of measurements they provide and thus in how accurate spatial localization can be.

Recently, high-density diffuse optical tomography, a form of optical brain imaging, was used to measure brain activity in listeners with cochlear implants while they listened to spoken words (Sherafati et al., 2022). The pattern of activity produced is summarized in **Figure 4**. Compared with controls, adult listeners with cochlear implants showed greater activity in the dorsolateral prefrontal cortex (part of the frontal lobe). These findings are notable because this part of the brain does not seem to be regularly engaged in speech comprehension. Instead, the dorsolateral prefrontal cortex is usually associated with executive tasks such as attention, decision making, and some forms of short-term memory. The implication of these findings is that because of the unclear acoustic signal, the brains of listeners with cochlear implants need to work harder to make sense of what they are hearing. This additional cognitive effort may interfere with higher level understanding or make it harder to remember what has been heard. However, it is worth noting that uncovering the brain systems supporting speech in listeners with cochlear implants is an active and relatively new area of research, and we expect our understanding to substantially evolve over the coming years.

Challenges to Speech Understanding from Face Masks

Although different types of face coverings have long been used in medical, industrial, and social contexts, widespread public health guidance regarding the benefits of face masks during the Covid-19 pandemic brought public awareness about face masks and associated communication challenges to a new level. Face masks challenge speech processing in at least two ways. First, the mask material partially blocks sound transmission, especially at higher frequencies, making speech not only potentially softer but obscuring specific speech cues. Second, opaque face masks prevent access to visual speech information from a talker's mouth, which is often relied on by listeners. The use of visual speech information is especially important for listeners with hearing loss or with a cochlear implant.

To look at how different kinds of face masks affected speech processing, people were asked to listen to sentences spoken by a talker with and without a mask (Brown et al., 2021). The sentences could be in quiet or in noise and were spoken with different face masks: a cloth mask without a filter, a cloth mask with a filter, a surgical mask, and a consumer transparent face mask, (**Figure 5a**). After each sentence, the people were asked to report the words they heard as a measure of their intelligibility and also to rate how difficult it was to understand the speech (as a measure of cognitive effort). Differences in performance were found depending on what kind of mask the speaker wore (**Figure 5b**). The surgical mask had the best performance, and the cloth mask with a filter and transparent mask performed the most poorly. Importantly, there were differences not only in speech intelligibility but also in the perceived effort associated with listening.

It is important to emphasize that Brown et al. (2021) tested a single type of clear face mask with listeners who reported normal hearing. It is very likely that for some listeners, visual speech information is crucial for effective communication; it is also likely that better clear masks exist rather than the one we tested. The data simply indicate that a clear

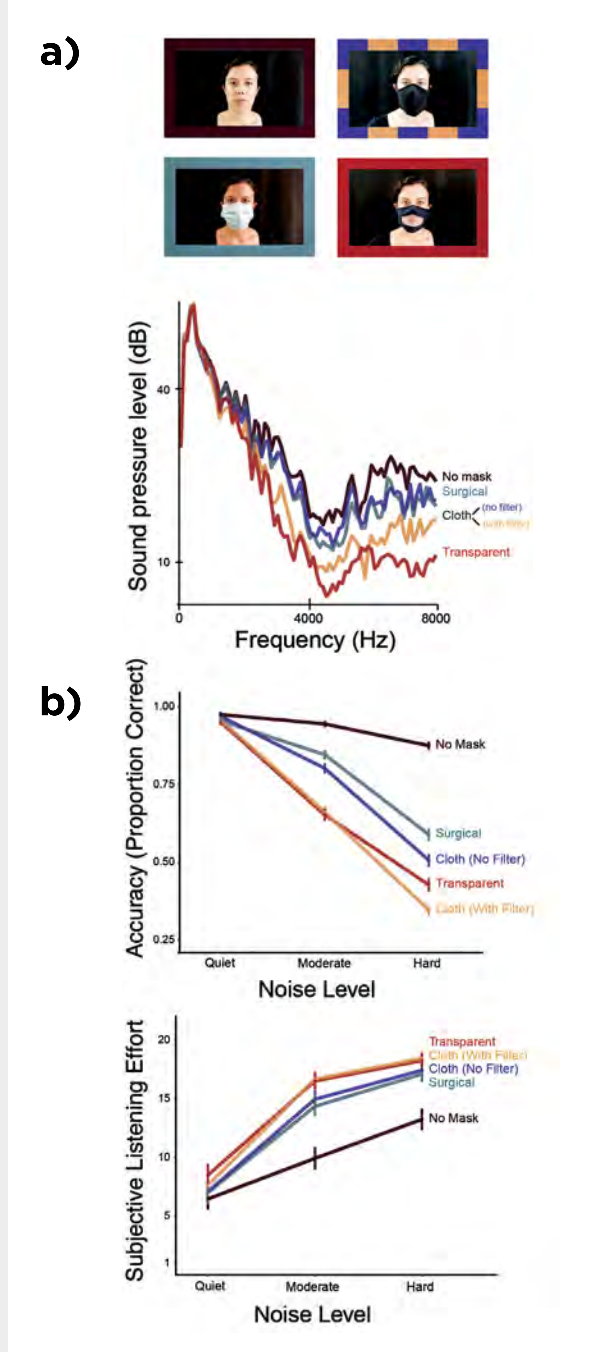


Figure 5. ***a:*** *Face masks tested (**top**) and the power at different frequency ranges (that is, the long-term average spectrum) of speech produced by these masks (**bottom**). The differences in the long-term average spectra indicate that different masks affect speech energy differently.* ***b:*** *Effect of face masks is larger in noise than in quiet, assessed both in terms of speech intelligibility (**top**) and how difficult listeners perceived the task to be, or subjective effort (here data from older adults; **bottom**). Adapted from Brown et al. (2021).*

mask is not *always* better for spoken communication and that other factors must be considered. And, indeed, in this study, N95/KN95 masks, which provide superior protection, were not evaluated.

How to Protect Hearing at Any Age and the Importance of Hearing Health Education

Hearing protection and monitoring ambient sound levels have seen increasing use in industrial settings in the United States and many other countries. An often-expressed concern, however, is potential effects on hearing related to the persistent high sound levels at many concert venues and with personal music players, especially among young adults.

Concern about sound exposure is heightened by studies showing that many young adults are unaware that they are beginning to have a hearing loss. The implications of these findings relate directly to our earlier mention that successful recognition of noise-masked speech comes at the cost of resources that would otherwise be available for encoding the words in memory. In an exploratory study, data obtained with university undergraduates who varied in hearing acuity were examined. All the undergraduates fell within a range typically considered in clinical audiology as normal hearing. The task involved the everyday experience of interpreting the meaning of spoken sentences. When the sentences expressed their meaning with a relatively simple syntax, interpretation accuracy was equivalently high for those at the higher and lower ranges of normal hearing. However, when sentences were presented that expressed their meaning with a more complex syntax, those with better hearing were more accurate than those with poorer hearing (Ayasse et al., 2019).

In addition to such behavioral effects, relatively small differences in hearing acuity among adults with normal or near-normal hearing manifest neural differences during sentence comprehension as well. Using fMRI, it was found that successful comprehension of sentences by individuals with poorer hearing was associated with greater recruitment (increased brain activity) in a right anterior middle frontal gyrus component of the frontoparietal attention network (Lee et al., 2018). These results demonstrate that even modest differences among individuals with clinically normal hearing affect the brain's response in the form of an increase in neural engagement of a non-sentence-specific component of the neural network to support successful sentence comprehension.

Thus, even slight differences in hearing acuity can have effects, however subtle, on everyday speech communication. At a practical level, these data argue for routine baseline hearing testing, even for young adults who currently have normal hearing. They also add to the growing support for an increased awareness of risks to hearing from extreme or prolonged noise exposure and, with it, increased use of hearing protection and noise reduction strategies.

Conclusions

Despite the challenges that a noisy acoustic signal presents for speech understanding, listeners' brains are able to engage additional cognitive systems to counter or at least mitigate the effects of noise on speech comprehension. However, doing so is not free but comes with a cognitive "cost": the increased processing needed for understanding speech may interfere with other mental activities, such as remembering what has been heard. Protecting hearing and, if needed, obtaining hearing health care, such as hearing aids, may thus have direct benefits for overall cognition.

At a broader level, studies such as those described in this brief review illustrate the general principle that the brain maintains stable functions (in this case, speech understanding) despite perturbations in the input (in this case, noise interference) by the flexible engagement of supporting neural networks. Speech comprehension, whether clear speech or speech in noise, must thus be understood as a dynamic and flexible interaction of the sensory, cognitive, and neural systems. The future of research and clinical practice in this area, we suggest, lies in our understanding of these interactions.

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