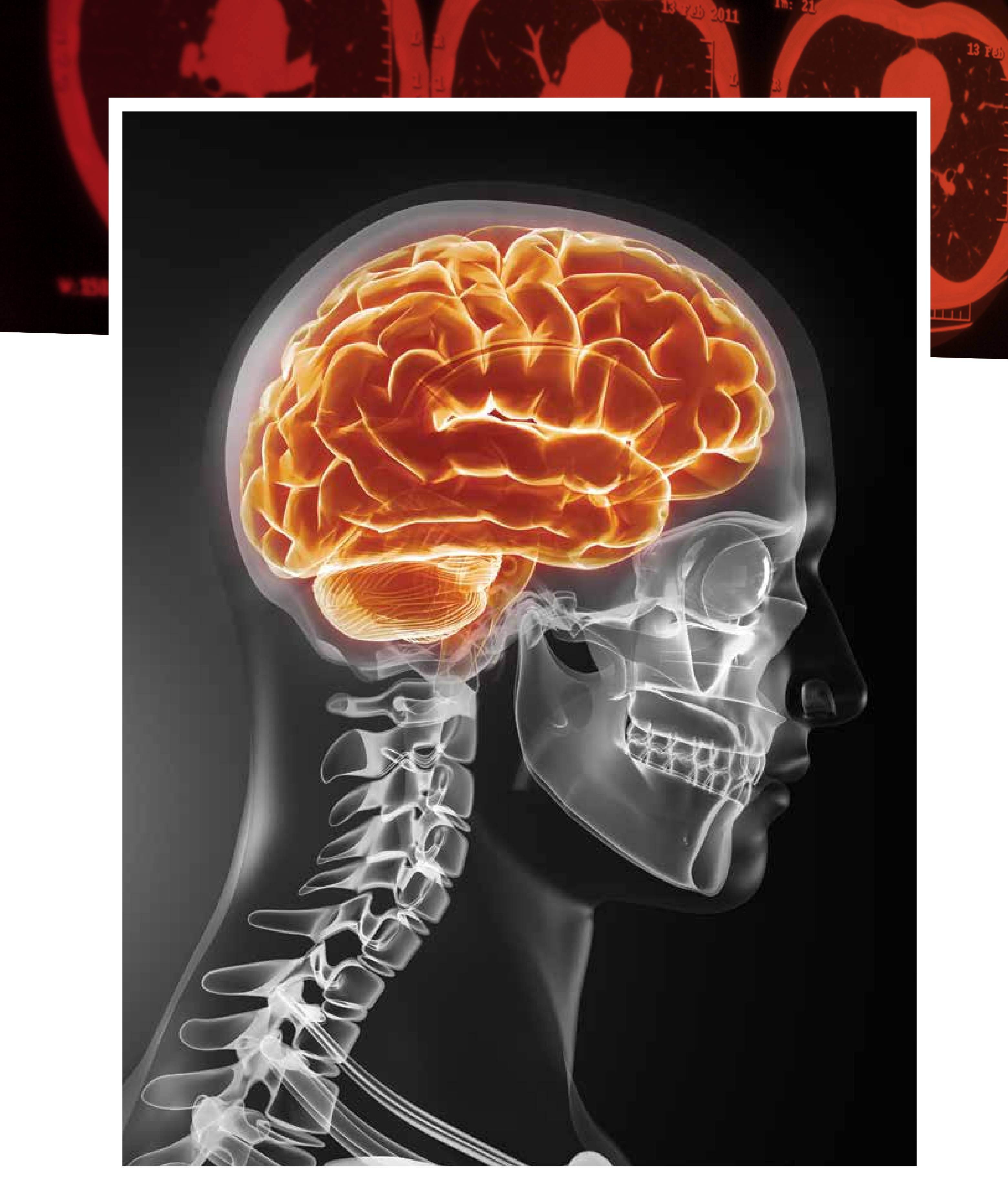
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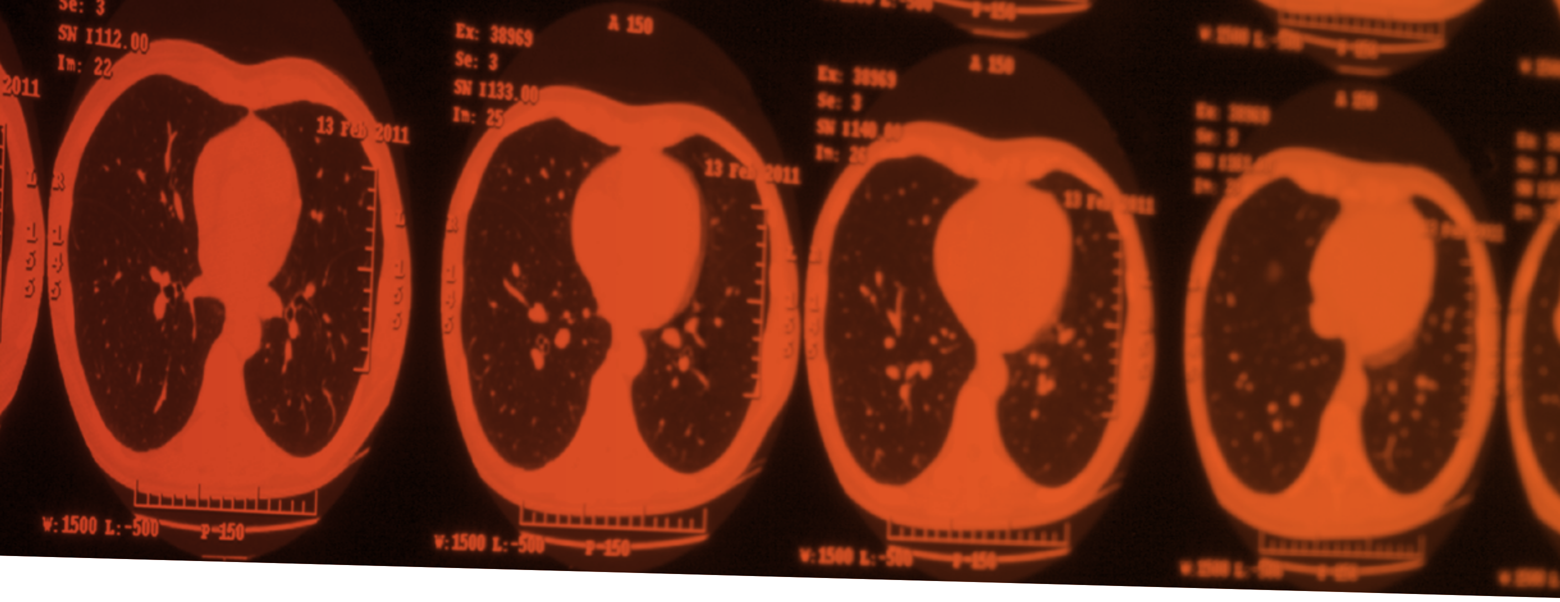

Brain Imaging, Neural Engineering Research, and Next-Generation Hearing Aid Design

BY ADRIAN K.C. LEE, MICHELLE K. DREWS, ROSS K. MADDOX, AND ERIC LARSON

Today's brain imaging and neural engineering research can influence future audiological practice—and next-generation hearing-aid design.

Dining in a crowded restaurant with your parents, among the bangs of cutlery and dishes, and the cry of a baby across the room, you are able to effortlessly concentrate on your mother's voice. Meanwhile, your father switches off his hearing aid because everything sounds like noise to him.

Listeners without hearing impairment can easily "tune in" to a sound of interest and "tune out" everything else in a crowded environment—just as one can focus during a conversation at a cocktail party. (The term "cocktail party effect" was first coined by E. Colin Cherry in 1953.) However, listeners with hearing loss facing multiple sound sources often find such situations overwhelming and intimidating (Noble and Gatehouse, 2006). Hearing aids, especially bilateral aids (Walden and Walden, 2005; Noble, 2006), can help, but many users find it difficult to interact in social settings because they cannot focus on one conversation while filtering out other unwanted sound (Gatehouse and Akeroyd, 2006; Shinn-Cunningham and Best, 2008). One of the top complaints for hearing-aid users is that they do not benefit from their aid(s) in noisy situations (Takahashi et al, 2007). This problem may be alleviated as engineering solutions are found for the design of next-generation hearing aids.

This article will introduce and summarize some of the latest brain-imaging studies that aim to uncover the neural underpinnings for auditory attention in the human cortex (FIGURE 1). We will highlight new neural engineering approaches that seek to translate these neuroscience discoveries into a next-generation hearing aid design and will conclude by speculating what could be available in audiology clinics at 5-, 15-, and 25-year horizons.

An Ideal Hearing Aid Design

Current hearing aid designers generally concentrate on developing sophisticated digital signal-processing strategies to improve speech intelligibility (Loizou and Kim, 2011) and speech quality (Hu and Loizou, 2007). This can help users to understand sound better in quiet. In addition, these speech enhancement strategies can help users to selectively amplify sound of interest in a multi-source environment. However, speech enhancement algorithms only work well when the suppressing noise sources are relatively constant, for example, a fan "humming" in the background.


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FIGURE 1. A cocktail party in action. In this illustration, spatiotemporal cortical activation clusters corresponding to the right temporoparietal junction (RTPJ; brain on the left) and the auditory cortex (brain on the right) are shown to highlight their participation in attending to different conversations in a cocktail party environment.

Directional amplification selectively amplifies in the direction one is facing (Ricketts, 2005), with no consideration of the current goal or desired focus of the listener's attention (e.g., eavesdropping). A more sophisticated algorithm could automatically steer a microphone toward a particular signal in the environment based on some simple rules regarding salience or other features, but the listener still would not have control. In everyday settings, hearing aid users are left with the daunting task of selecting speech that can originate from many different directions. Current hearing aid technology alone is not equipped to provide proper assistance.

For improved hearing-aid design, Shinn-Cunningham and Best (2008) suggested that "a revolutionary assistive listening device would use robust source separation algorithms to create auditory objects…and emphasize the desired target of attention…[while] enabling the listener to selectively attend, at will, to different objects in the environment." While existing computational auditory scene analysis cannot yet segregate speakers or other sound sources as well as listeners without hearing impairment, this is an active research area (Wang and Brown, 2006). Despite this challenge, there are neural engineering approaches that aim to dynamically incorporate the user's intention to work toward a revolutionary "next-generation" hearing aid that selectively amplifies signals of interest.

Feed-Forward to Feedback Design

Devising a hearing aid that incorporates the user's intention requires a fundamental paradigm shift in hearing-aid design, moving away from a feed-forward amplification to a system incorporating a feedback loop.

The choices related to the creation of an apple pie can illustrate these concepts (FIGURE 2). We have a basket of apples—most are ripe, but a few are rotten—containing a mixture of different types: Granny Smith, Golden Delicious, and Honeycrisp. There are many ways to make our apple pie. An unsophisticated approach (let's call this Method 1) would be to include all the apples indiscriminately. A more prudent way (Method 2) would be to throw the rotten apples out first. With no knowledge of our diners' taste preferences, we would simply use all the apples, so that the pie would be neither too sweet nor too tart. Of course, the best pies are made to a diner's specification

(Method 3), that is, the baker would make individual pies after asking each diner about the kind(s) of apple he or she prefers. In addition, each type of apple could be accompanied with a complementary addition such as cheddar cheese with Honeycrisp and ice cream with Granny Smith.

The process of selecting apples for our pie(s) is not dissimilar to the way different hearing aid strategies could amplify sounds. In pie making Method 1, no consideration was given to whether the selected apples were rotten or not. This is similar to the simplest hearing aid strategy, where all sounds are amplified, regardless of whether they contain speech, background noise, or both. In Method 2, the baker selectively threw out the rotten apples. This is akin to the noise-reduction strategies currently employed in most hearing-aids—incorporating state-of-the-art signal-processing techniques to adaptively filter out noise, thereby improving the signal-to-noise ratio (SNR). However, if an individual wants to have an apple pie containing only Granny Smith apples, Method 2 will not suffice. Only by incorporating the specific user's feedback (Method 3) can we be sure to make an apple pie tailored to that individual. In a multitalker environment, there

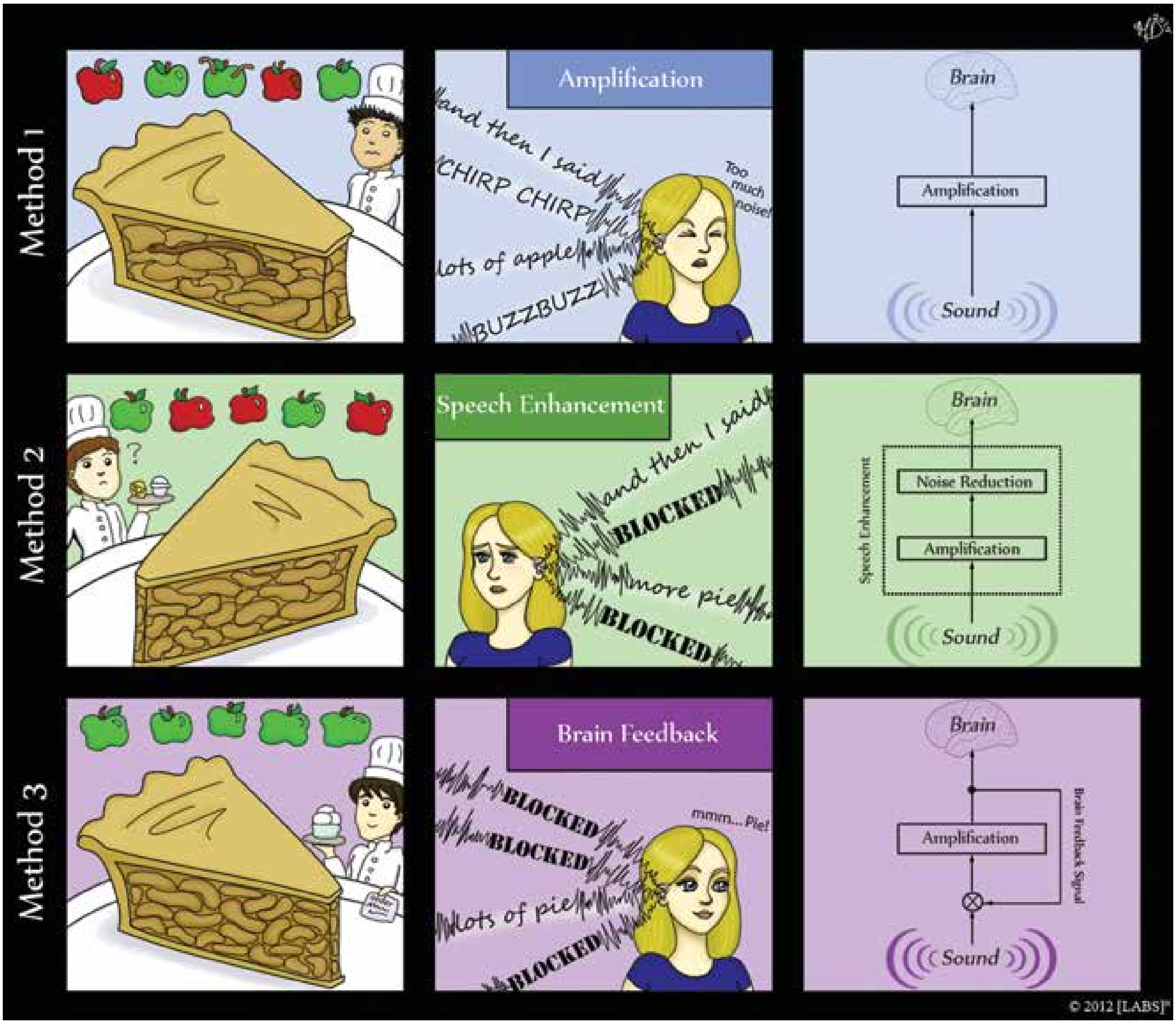

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FIGURE 2. Differing ways of baking an apple pie (left column) as an analogy to illustrate amplification strategies used in current hearing aids (middle and right columns).

are many different speech sources the user may want to attend (and the focus of attention can dynamically switch among talkers). It is only by incorporating the user's intention that a hearing aid can truly amplify the sound of interest and suppress other uninteresting sources.

Current Brain-State Classification and Brain-Computer Interface (BCI) Technology

How do we dynamically track a user's intention? By reading their mind? This may not be as far-fetched as it initially seems. Harnessing the capability of reading and classifying brainwaves into the myriad possible cognitive states (referred to as brain-states) has been a long-standing engineering challenge. Brain signals generally are captured noninvasively by electroencephalography (EEG), an inexpensive and portable tool that records the brain's electrical activity by measuring electrical potentials on the scalp. The current deployment of brain-state classification using EEG mainly falls into two categories: (1) diagnosis of neurological disorders or (2) capturing the user's intent to augment, alter, or restore function through a brain-computer interface (BCI; e.g., using thoughts alone to control a wheelchair or a speech synthesizer).

In clinical research, many studies have investigated the feasibility of using EEG to diagnose conditions such as Alzheimer's disease (Dauwels et al, 2010), autism (Bosl et al, 2011), and potentially, schizophrenia, depression, and other conditions (Begic et al, 2011). In addition, EEG event-related potentials (ERPs) have been used to assess sensory and cognitive aspects of central auditory processing (Patel and Azzam, 2005; Alain and Tremblay, 2007). In the emerging

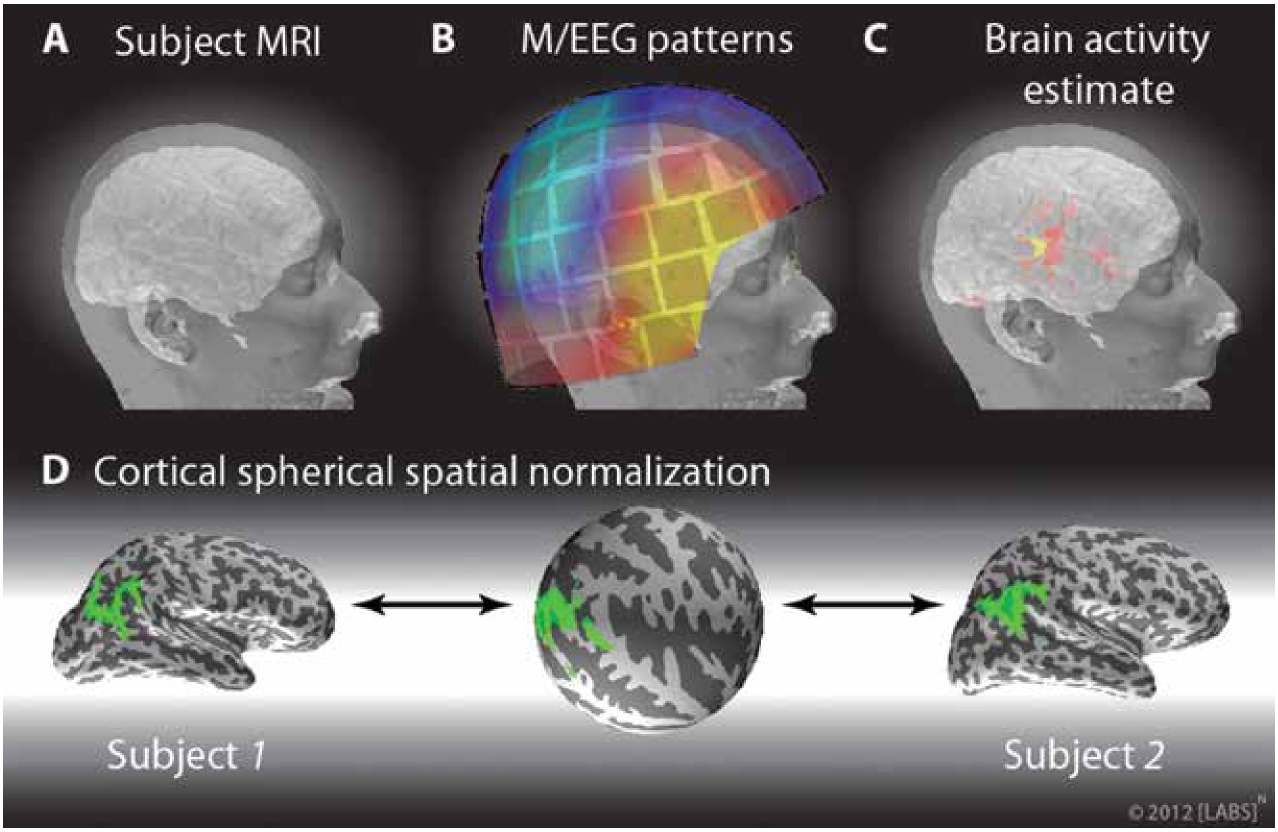


FIGURE 3. To reveal the timing, as well as the cortical regions responsible for different cognitive tasks, we combine (A) anatomical information captured by using an MRI scan with (B) M/EEG signals to estimate (C) neuronal activities in the brain. (D) To account for structural differences, a spherical cortical spatial normalization procedure is used.

field of neural engineering, there are approximately 300 laboratories internationally focusing on BCI research (Guger, 2011). The majority of groups focus on developing systems that serve the needs of those with severe neuromuscular disabilities. For example, the first P300-based BCI typewriter (named after a positive deflection of the EEG ERP at 300 ms that reflects a person's reaction to a presented stimulus) was first proposed 25 years ago (Farwell and Donchin, 1988). This technology aims to provide paralyzed individuals with a way to communicate with their environment again through a direct connection between the brain and the external world (Schreuder et al, 2011).

Neuroscience and BCI Technology

To dynamically control a hearing aid, we need to understand when and which part of the brain is active, so that we can use these signals as feedback to control the auditory filtering. While the EEG-ERP approach may provide the temporal evolution of cortical signals, the spatial resolution is relatively poor and, thus, makes it difficult to "tune into" specific cortical regions. In our laboratory, we combine magnetoencephalography (MEG, the magnetic brain-imaging counterpart to EEG), EEG, and anatomical information acquired using magnetic resonance imaging (MRI) to reveal the timing as well as the cortical regions that are responsible for coordinating different cognitive tasks (e.g., when a listener just switched his or her attention to another speaker) (FIGURE 3) (Lee et al, 2012).

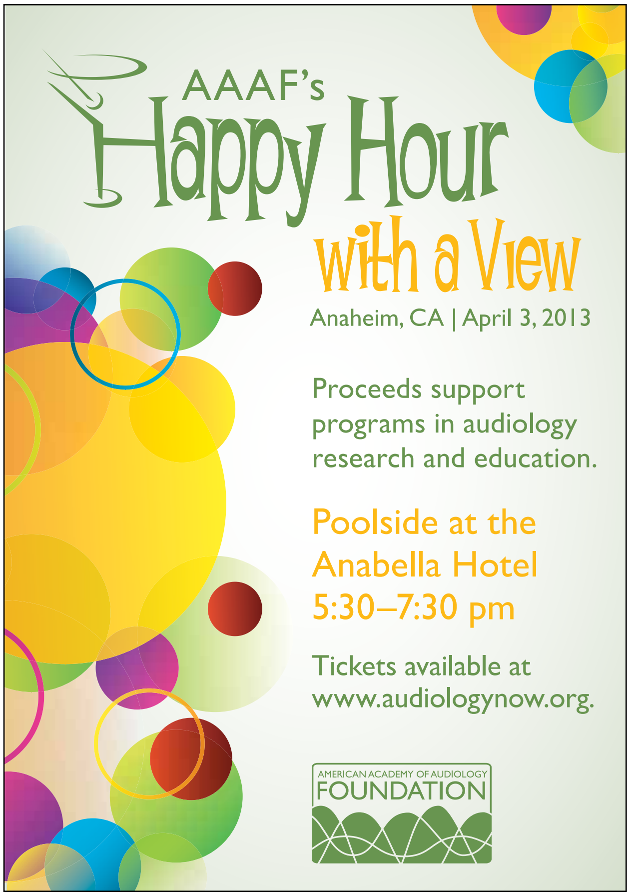
Every human brain is unique. To compare structural and functional properties across subjects, we must translate brain structures from different participants into a common reference frame, known as cortical spatial normalization (Ghosh et al, 2010). This is a routine procedure used in many brain-imaging studies. This spatial normalization needs to be taken into account to make BCI perform favorably across subjects (Larson and Lee, 2011) because the different geometrical folding of individual brains influences the brain-activity pattern measured on the scalp. This is currently an active area of research; whether individualized anatomical information is essential for BCI deployment (in a "next-generation" hearing aid design or other applications that rely on brain feedback) will become clearer in the coming years.

Neural Signatures for Future Hearing Aid Control

There are many relevant brain-states that must be identified to tune a hearing aid based on user's intention. One of these is whether the user has switched attention from one speaker to another.

In a recent neuroimaging experiment (using MEG, EEG, and anatomical information), we investigated the neural correlates of this attention-switching signal in the cortex (Larson and Lee, 2013). In this task, subjects reported one of two distinct auditory tokens (spoken numerals, one through four), presented simultaneously in each trial. Each token was played over headphones to sound as if it originated from 30 degrees left or right of midline. In one-third of the trials, the subjects were asked to switch attention (via a visual cue) to the opposite hemifield from the originally cued side, and in two-thirds of the trials, they were cued to maintain attention on the originally cued side.

A cortical region, commonly referred to as the right temporoparietal junction (RTPJ), was found to be more engaged in switched than nonswitched trials. In addition, there was a strong correlation between the subjects' behavioral performance and their RTPJ activation. Cortical mapping of both auditory and visual attention in these types of tasks (Shomstein and Yantis, 2006; Knudsen, 2007; Corbetta et al, 2008) remains an active



research area, and we are hopeful that work in the coming decade will reveal many more neural signatures that will be viable candidates for incorporation in BCI technology, specifically aimed for designs in hearing aids.

Future Hearing Aid Design: 5-, 15-, and 25-Year Horizons

It may still be a decade or two before the ideal BCI-based hearing aid design can be deployed in the field, but there are potential technologies that can be incorporated in the short-term that could step closer to a selective-tuning hearing aid based on user intent.

One technology that might be available within five years is based on a recent invention for a "self-steering directional hearing aid" that was filed in the U.S. Patent Office (US 2010/0074460 A1). This patent describes technology that can be used to steer the direction of a microphone based on a user's eye gaze position, detected by sensors (perhaps incorporated into a pair of glasses). This type of technology would provide a short-term solution to enable hearing aid users to have control of the spatial-amplification profile of their devices.

Combining the development in speech enhancement technology with the active research in computational auditory scene analysis may prove fruitful in improving speech intelligibility. It is conceivable that such technology will be incorporated in most digital hearing aids in 15 years.

Hearing aids with EEG-BCI feedback control are likely to be available at a 25-year horizon. It is also likely that EEG sensor and hardware development will have improved to the point that sensors can be applied "seamlessly" to a user's head (perhaps via a cap) without the present constraints of wires and messy conducting gel.

We will undoubtedly encounter many challenges as we march toward this brave new world of a next-generation hearing aid design. We are hopeful that, by combining the fields of neuroscience and engineering, we will eventually enable hearing aid users to fully and effortlessly engage in conversations in their daily lives.

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