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How to assess the corollary discharge in humans using non-invasive neurophysiological methods

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SUMMARY

We present a vocal production protocol for studying the neurophysiological action of the corollary discharge, a mechanism that allows animals to ignore sensations resulting from their own actions, and tag them as “self”. EEG is recorded while subjects say “ah”, about 100 times, with minimal throat, jaw, and tongue movements (Talk condition). This sequence of sounds is recorded and played back during the Listen condition. Event-related potentials (ERPs) are synchronized to the onset of speech sounds during the Talk and Listen conditions. Neural responses from auditory cortex to the spoken sound *as it is being spoken* during the Talk are compared to the neural responses to the same sounds when played back during the Listen condition. The successful action of the corollary discharge is seen when the response of auditory cortex is suppressed during the Talk compared to the Listen condition. The protocol takes about 5 minutes to complete.

INTRODUCTION

All animals need to be able to distinguish between sensations resulting from their own actions and those resulting from the actions of others¹. Nature’s mechanism for making this critical distinction between “self” and “other” is implemented in the corollary discharge mechanism. Such a mechanism was first described by Helmholtz as a system enabling the discrimination between moving objects and movements on the retina resulting from eye movements². This is known as saccadic suppression and is demonstrated by comparing the visual image during a saccade to the visual image experienced when the eye is externally moved, by tapping it in the corner. Others later suggested that this suppression was accomplished through the action of an efference copy³ or a corollary discharge⁴.

Though this mechanism is ubiquitous, and its actions are seen in animals, from nematodes to human and non-human primates, its neural basis has only recently been described¹. Poulet and Hedwig⁵ recently explained how the corollary discharge allows the cricket to sing at deafening intensities without deafening itself. Sommer and Wurtz⁶ described how the corollary discharge enables the visual image projected to visual cortex to be stable in spite of

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the monkey's eyes darting about the visual scene. In their recent review article, Crapse and Sommer¹ concluded: "In addition to the usual flow of information from sensory systems to motor systems, there is extensive signaling in the opposite direction by motor systems reporting their activities to sensory structures. It is this coordination between the two systems that makes it possible to analyse the world while moving within it." That is, the traditional stimulus → response paradigm can be flipped on its head and become the response → stimulus paradigm. By studying the brain's response to its own self-generated stimuli, we can see the organism as integral to its environment with which it interacts.

In the primate auditory system, efference copies from speech and vocalization regions in the frontal lobes may prepare the auditory cortex for the imminent arrival of self-generated sounds, minimizing the auditory cortical response to these sounds and providing a mechanism for recognizing these sounds as self-generated (See Figure 1). Support for this mechanism comes from studies by Creutzfeldt and colleagues in which recordings were made from human patients during pre-surgical planning from the exposed surface of the right and left temporal cortices while they talked and listened to others talking; suppression of activity in auditory cortex was noted during talking compared to listening⁷. Similarly, Eliades and Wang^{8, 9} recorded from primary auditory cortex single units in marmoset monkeys during vocalization, and they reported vocalization-induced suppression beginning before vocalization, with excitation of different units beginning after vocal onset⁹.

In a later paper where they altered the pitch of auditory feedback during vocalization¹⁰, Eliades and Wang reported that auditory neurons, which were suppressed during normal vocal feedback, showed a larger increase in firing rate in response to pitch-altered feedback than those neurons that were excited during normal vocal feedback. They suggested that the vocalization-induced suppression enhanced neural sensitivity to feedback perturbation. In a similar study with humans using scalp recorded EEG, Behroozmand and colleagues¹¹ also showed an enhanced auditory sensitivity to altered feedback during talking. These studies suggest that the corollary discharge mechanism not only suppresses responses, but also provides more specific modulation for self-monitoring. Eliades and Wang (2008) pointed out that this is useful for discrimination between self-generated and external sounds, as well as vocal convergence, allowing monkeys to match their vocalizations to their cage-mate's¹².

While the neurobiology of the corollary discharge/efference copy mechanism has been elegantly described across the animal kingdom, fewer laboratories have attempted to study it in humans^{13, 14}, perhaps because of the artifacts talking produces in the scalp-recorded EEG. We have overcome most of the problems encountered with data acquisition and artifacts in human studies, and have developed EEG-based neurobiological assays to study the efference copy/corollary discharge mechanism, non-invasively, in human volunteers^{15–19}. In all these studies, we report suppression of auditory cortex during vocalization in healthy controls, as seen in a reduction of the N1 amplitude of the event-related brain potential (ERP) to the onset of the spoken sound *as it is being spoken*. This provided a direct test of the corollary discharge and was similar to methods used by others with human^{11, 13, 14} and non-human primates^{8, 9}. We, and others, suggest that this suppression results from a match between the corollary discharge and the sensory re-afference^{13, 14, 8, 9}. And, as suggested by

studies which alter vocal feedback during vocalization, the closer the match the greater the suppression¹⁷.

Applications of the method

In 1978, Feinberg²⁰ suggested that dysfunction of this mechanism may underlie the positive symptoms of schizophrenia. In 1987, Frith²¹ expanded this concept and prompted a series of behavioral experiments confirming corollary discharge dysfunction in schizophrenia^{22–27}. Neurophysiological evidence for dysfunction of the corollary discharge system in schizophrenia has been documented in auditory^{15, 16, 18, 19, 28, 29} and somatosensory modalities^{25, 30, 31}. Using the N1 component of the ERP in the talking/listening paradigm described here, we find that the normal dampening of the auditory cortical response during talking or inner speech is less evident in patients with schizophrenia^{15, 16, 18, 19, 28, 29}.

While our main interest has been in understanding schizophrenia, application of this paradigm might reveal deficits in corollary discharge in movement disorders, such as Parkinson's disease and communicative disorders, such as aphasia and stuttering. Indeed, the corollary discharge mechanism may be responsible for feedback-mediated vocal control, and defects in feedback monitoring have been suggested to underlie human communication disorders such as stuttering³². In the same vein, this vocal production protocol might also be used in studies of language learning and vocal mastery.

There are a number of possible variations of the protocol that may provide useful data on how humans respond to sensations resulting from their own actions. As mentioned above, we¹⁷ and others^{11, 33} have shown that feedback to the subject can be altered in pitch during vocalization. As mentioned above, these studies highlight the precision of the corollary discharge mechanism by showing less suppression of auditory cortex when what you say does not match what you hear. Others have also varied the rapidity and complexity of the speech and shown that more rapid and complex speech produces less suppression of auditory cortex, possibly because of the amount of attention that must be paid to produce and monitor rapid and complex speech³⁴. Other manipulations with this paradigm could include subtle temporal delays between vocal onset and the arrival of side-tones to the ear (i.e., delayed auditory feedback), which could provide useful data on the temporal precision of the corollary discharge. Because sounds reach the inner ear via air and bone conduction, and because bone conduction of the sounds cannot be delayed, this is best done with whispering, which does not involve bone conduction. (See discussion of bone conduction below.)

Comparison with other methods used to study corollary discharge in humans

Behavioral studies of the corollary discharge have produced a wealth of data explaining, among other things, why we can't tickle ourselves^{35, 36} and why we hit back harder than we were hit³⁷. While elegant and descriptive, they do not provide temporal information about the timing and duration of suppression of the sensation, which must be quick and brief and not outlast the movement itself, or the animal would be rendered impaired and vulnerable. Thus, biological methods that allow the instantaneous assessment of its action, such as EEG and MEG (electro- and magneto-encephalography), can provide direct measures of the

neural activity with unlimited temporal precision. They suffer, however, from a relative lack of spatial precision. fMRI methods provide superior spatial resolution but poor temporal resolution. Perhaps because of the short duration of action of the corollary discharge, our efforts to use fMRI to study the corollary discharge during talking have been disappointing³⁸. In addition, MR scanners are also very noisy, even between acquisitions using clustered acquisition protocols. The noisy environment may produce compensatory speech, as it is well-known that people speak louder when the environment is loud, or the Lombard effect³⁹. Such compensation may also affect auditory cortical suppression during talking.

Experimental Design

Our basic “Talk/Listen” paradigm has two conditions: Talk and Listen. For the Talk condition, we record EEG while the subject “talks” (says “ah”) for a couple minutes. The speech channel is continuously recorded during the Talk condition for unmodified playback during the Listen condition. We insert trigger codes in the EEG at the onset of each speech sound. EEG epochs, time-locked to the onset of the “ah”, are averaged together to produce an ERP. The most dominant feature of this ERP is the N1, a negative component peaking at about 100ms after the onset of the sound. Although it emanates from auditory cortex, N1 is best measured at the frontal-central midline sites because of the geometry of the brain and volume conduction of neural signal from auditory cortex to the vertex of the head⁴⁰.

Electrode Cz is located at the vertex when using the international 10–20 electrode placement system, and nearby midline electrodes, FCz, CPz, and Fz, could form a minimalist 4-electrode recording montage, while more elaborate and dense recording montages could be employed to facilitate source modeling (See,⁴¹ for review). Depending on the recording system, a single electrode may need to be selected as a recording reference, and we recommend recording right and left earlobe or mastoid electrodes independently to serve as algebraically linked references during offline processing. The nose electrode is not recommended because excessive artifacts may be generated during the Talk condition due to facial muscle movement. Collection of electro-oculogram (EOG) data to detect vertical (blink) and horizontal (saccade) eye-movements can be achieved by placing electrodes above and below the right eye (VEOG) as well as on the outer canthi of right and left eyes (HEOG). Acceptable electrode impedance levels depend upon the particular EEG system used (i.e. less than 5 kOhm for Neuroscan Synamps), but new EEG researchers should take advantage of training and best practice recommendations available from system vendors. Regardless of which EEG system is used, researchers should attend to any change in impedance or electrode offset throughout the task recordings, making necessary adjustments to maintain equivalent levels during both Talk and Listen conditions.

Controls

It is important that intensity be equated across Talk and Listen, as N1 is exquisitely sensitive to intensity. In a more natural setting than we use, while subjects talk, they would hear side-tones coming in through their ears, and they would hear recorded speech through earphones during Listen. Equating intensities in this more natural setting would involve matching intensity of the side-tones at the ear during Talk to the intensity of the recorded speech at the

earphones during Listen, a tricky procedure. Instead, we use earphones during both Talk and Listen, and amplify the sound the same amount during both conditions (see Heinks et al for data collected this way¹⁷).

Although not essential, amplifying the sound during Talk also mitigates against contamination from bone conduction. Bone conduction might increase the loudness of the spoken sound and could possibly produce a *larger* N1 during talking. This would work against showing suppression of N1 during talking, making our finding of suppression more compelling. To completely avoid bone conduction, we have also pilot-tested a whisper version of this task in which we ask subjects to whisper “ah” instead of vocalize it. We get excellent suppression of N1 during whispering compared to when that whispered sounds are played back. Finally, bone conduction can be completely avoided by using a button press to deliver a tone^{42–45} or a speech sound¹⁵. While the auditory cortical response to the sound is dampened when self-delivered with a button press, the amount of suppression is considerably greater when subjects are speaking¹⁵.

Regarding sound fidelity, we recommend a sound card that supports 24-bit input and output. However, because not all software is compatible with that, the conditions described below record and playback 16-bit sounds. While not ideal, any degradation of the sound frequency spectrum due to 16-bit recording and playback should be equivalent across Talk and Listen conditions.

Although we have implemented the two different versions of the Talk condition described below, the Self-paced version (#2) is what we describe in this protocol:

1. Cued: Each “ah” utterance is cued by a yellow “X”¹⁶ or other visual stimulus¹⁷. This controls the speed of talking, but can introduce overlapping ERP components from the cue, depending on the time between the cue and speech onset.
2. Self-paced. This has no overlapping component issues, but does have uncontrolled inter-ah intervals. However, after a short practice, subjects are able to generate between ~75–125 “ah” utterances in several minutes, making it an efficient version of the task and ideal for time-frequency analysis.

While these are two different examples of methods used to assess corollary discharge during simple vocalization in humans, both are blocked, and the Talk condition always comes before the Listen condition. This could lead to potential confounds as attention or arousal level may shift between the task blocks. Short recording blocks, as well as ample breaks and instructions to participants between blocks, should help reduce such shifts. However, it is possible to record an interleaved task, where each cued “Talk” trial is followed by its playback (version #1). Interleaving the self-paced version (#2) would be more challenging because Talk and Listen condition trials could potentially overlap, but such an implementation is possible. While these designs should avoid problems of differential arousal levels during Talk and Listen conditions, differential attention can vary from moment to moment and cannot even be ruled out of an interleaved design.

MATERIALS

Human Subjects

CAUTION: Obtain informed consent from research subject

Equipment

1. Human EEG acquisition system (e.g. Neuroscan, [BioSemi](#)) and consumable EEG supplies
2. Stimulus presentation computer (e.g. [Dell Desktop](#)) with PCI slot, parallel port, dual video output, and two monitors (one for subject and one for investigator)
3. Peripheral Component Interconnect (PCI) sound card (e.g. [Sound Blaster X-Fi XtremeGamer](#))
4. Insert Earphones (e.g. Etymotic [ER-1/ER-3](#)), appropriate stereo connectors (see Equipment Setup), and disposable foam ear insert tips
5. Microphone, appropriate stereo connectors (see Equipment Setup), and microphone stand

Equipment Set up

A schematic illustration of the set up is shown in Figure 2.

EEG-stimulus interface (Figure 2)

The stimulus presentation computer must be connected to the EEG acquisition system to facilitate the insertion of time stamps (triggers), allowing for stimulus-locked data processing offline. Most systems (e.g. Neuroscan, BioSemi) receive triggers via a cable included in the purchase of the system, which connects to the 25-pin, parallel port on the stimulus presentation computer. This represents the only direct connection between the EEG acquisition system and the stimulus presentation computer.

Sound Input/Output (Figure 2)

The stimulus presentation computer should contain at least one available PCI slot to support the sound card. While multiple PCI sound cards are available for purchase, the Sound Blaster X-Fi XtremeGamer is the only PCI card currently available that has been tested by our lab and shown acceptable performance characteristics (i.e. less than 1ms lag). The sound card will have one input and one output used during the experiment. The microphone connects to the input, and adapters are often necessary to convert its cable to a 1/8" male stereo jack. The insert earphones connect to the output, and a dual mono 1/4" female to stereo 1/8" male adapter is necessary to connect the Etymotic ER-1 earphones to the soundcard. A stereo 1/4" female to stereo 1/8" male adapter is necessary to connect the Etymotic ER-3 earphones to the soundcard. Headphones placed directly over the ear are not recommended because the phones and headband that connect them place pressure on the electrodes and the electronics in the phones can both create artifacts in the EEG recording. If

headphones placed on the ear must be used, padded headphones, or headphones that do not require a headband, will minimize artifacts related to pressure or tension on the head. Windows XP sound settings must be changed to monitor microphone input (see video S1).

Video Output (Figure 2)

The stimulus presentation computer should have dual video output or a connected video splitter with one monitor in the subject testing area and one monitor in the experimenter recording room. In the case of a dual output video card, the video signal should be “cloned” by selecting this feature in the appropriate software control panel. Depending on the layout of the testing area, video and audio extension cables may be required.

Subject Area

Replace the foam ear insert tips before every test session and place microphone on microphone stand in front of subject chair in the EEG testing room.

PROCEDURE

Set up

Timing: approximately 20 to 60 minutes, depending on EEG system and recording montage

1. Prepare research subject for EEG recording using any data acquisition system (e.g. BioSemi, Neuroscan, EGI, BrainProducts) that accepts event triggers from an external stimulus presentation computer
2. Place foam tips of insert earphones in subject's right and left ear canal, pulling up gently on the earlobe to ensure proper insertion
3. Test the microphone, confirming the subject can hear through the foam ear inserts (See, Troubleshooting Table)
4. Display subject's continuous EEG on a video monitor
5. Ask subject to blink a few times rapidly and point to the resulting ocular artifacts in the EEG
6. Ask the subject to clench jaw and describe the “thick” EEG lines as unwanted muscle artifact (Figure 3 top), whereas the thin EEG lines are the brain signals of interest (Figure 3 bottom)
7. Confirm that the subject understands eye-movements, such as blinking (Figure 3), and muscle movements, such as jaw clenching, eye-brow raising, or even smiling contaminate the EEG signal

Get ready to record

Timing: approximately 5 minutes

1. Present Talk condition instructions
 - A. Matlab option (zip S1)

- i. Play Talk condition instructions movie file in QuickTime (video S2)

B. Presentation option (zip S2)

- i. Play Talk condition instructions scenario in Presentation
2. Review instructions with subject, answering any questions about the task
 3. Ask subject to find a comfortable seated position, which can be maintained for 3 minutes
 4. Place the microphone 2 to 3 inches in front of subject's mouth
 5. Ask the subject to practice the task, saying "ah" every 1 to 2 seconds until told to stop
 6. Check the intensity of subject's "ahs" using a handheld deciBel (dB) meter set to "fast" mode, positioning the meter as close the microphone as possible
 7. Monitor the dB readings and the pace (inter-"ah"-interval) for 5 "ahs", using a watch or clock if available. Target feedback to produce about one "ah" every 1 to 2 seconds, at 75–85 dB.
 8. Monitor the EEG recording for 5 to 10 "ahs", searching for gross artifacts related to the subject's head, jaw, or chest movement (a second researcher can do this during step 7). Target feedback to produce movement- and muscle-artifact free EEG
 9. Inform the subject that the task is about to begin
 10. Remind the subject to do the task as practiced, beginning when the plus sign appears on the screen

Recording

Timing: approximately 10 minutes

1. Run the Talk condition

A. Matlab option

- i. Launch Matlab
- ii. Move into the Psychtoolbox directory
- iii. Type "talk" on the command line to start the run
- iv. Enter information when prompted until "Ready" message appears

B. Presentation option

- i. Launch Presentation
- ii. Run the "Talk.sce" scenario
- iii. Wait until a "Ready" message appears

2. Start an EEG recording file (only BioSemi EEG system described in the remaining steps)
3. Press “Enter” key on the stimulus presentation computer (this initiates both Presentation and Matlab versions of the task)
4. Confirm that EEG data and triggers are recording (Critical: data analysis will be impossible without triggers)
(See, Troubleshooting Table)
5. Monitor continuous EEG recording for excessive muscle, sweat, or movement artifacts
(See, Troubleshooting Table)
6. Confirm that the Talk condition completed and EEG recording has been paused
7. End EEG file recording by clicking “stop file”
8. Switch the microphone off or mute the microphone in the sound control panel
9. Present Listen condition instructions
 - A. Matlab option
 - i. Play instructions movie file in QuickTime (video S3)
 - B. Presentation option
 - i. Play instructions scenario in presentation
10. Review instructions with subject, answering any questions about the task
11. Run the Listen condition
 - A. Matlab Option
 - i. Type “play” on the command line to start the run
 - ii. Enter information when prompted until “Ready” message appears
 - B. Presentation Option
 - i. Run the “Listen.sce” scenario
 - ii. Wait until “Ready” message appears
12. Start an EEG recording file
Press enter on the stimulus presentation computer (this initiates both presentation and Matlab versions of the task)
(See, Troubleshooting Table)
13. Confirm that EEG data and triggers are recording (Critical: data analysis will be impossible without triggers)

14. Monitor continuous EEG recording for excessive muscle, sweat, or movement artifacts
15. Confirm that the Listen condition completed and EEG recording has been paused
16. End EEG file recording by clicking “stop file”
17. Remove EEG cap from subject

Post-recording

Timing: approximately 30 minutes

1. Clean/disinfect cap and electrodes in accordance with local IRB approved procedures
2. Copy all experiment data files to appropriate location and run speech-onset picking Matlab script (zip S1 or zip S2)
 - A. If programming script outside of Matlab programming language:
 - i. Load speech data (.wav file)
 - ii. Rectify the speech data (calculate the absolute value of every sound data sample)
 - iii. Z-transform the rectified samples, converting to z-scores
 - iv. Apply ~70Hz low-pass filter to the data
 - v. Identify “ah” onsets searching for a slope greater than 0.0003. Confirm that the “ah” duration is at least 100ms and its mean amplitude is greater than 0.3. The Z-score at the onset should be greater than the 100ms preceding it to avoid marking one “ah” twice.
 - vi. Identify the latency of the first trigger time-stamp in the Talk EEG file, which marks the beginning of the speech sound recording (i.e. the first sample in the .wav file)
 - vii. Write a Talk condition speech-onset data file by taking the onset of each “ah” and adding the first trigger time stamp to it
 - viii. Identify the latency of the first trigger time stamp in the Listen EEG file, which marks the beginning of the speech sound playback (i.e. the first sample in the .wav file)
 - ix. Write a Listen condition speech-onset data file by taking the onset of each “ah” and adding the first trigger time stamp to it
3. Run speech-onset manual inspection and onset adjustment Matlab script (zip S1 or zip S2), adjusting onsets (Figure 4) and rejecting trials with onsets that are indistinguishable from background activity (e.g. Figure 4D)

4. Import inspected speech-onset latencies and EEG data into favorite ERP analysis software
5. Re-reference data to average of right and left mastoid or earlobe channels, depending on recording montage
6. Apply 0.5 to 15 Hz band-pass filter to continuous EEG data
7. Create individual trial epochs by segmenting continuous data from 100ms preceding speech onset trigger to 400 ms following it
8. Apply ocular correction to scalp EEG channels using favorite method (e.g. ICA, Regression-based, rejection)
9. Baseline correct individual trials by averaging the data points preceding speech-onset and subtract that average from every point in the epoch
10. Reject trials containing artifacts, measured as $\pm 50\mu\text{V}$ excursions occurring at any sample in the epoch for any EEG channel of interest (e.g. Cz)
11. Create an ERP for each condition by averaging across all remaining trials within that condition (Figure 5)
12. Search for the N1 by identifying the most negative peak between 60 and 150 ms following speech onset for both Talk and Listen conditions
13. Export the peak amplitude, area $\pm 25\text{ms}$ around the peak, and the peak latency for statistical analysis

ANTICIPATED RESULTS

We expect the N1 component of the ERP elicited by the spoken sound during the Talk condition will be significantly smaller (less negative) than during the Listen condition. This is illustrated in Figure 6, and has been shown previously by us^{15–19} and by others^{13, 14}.

We believe suppression of N1 during talking is a reflection of the successful action of the corollary discharge, working to suppress cortical responsiveness. The corollary discharge is a neural signal that accompanies all actions and prepares sensory areas of the brain for the arrival of sensations resulting from the animal's own actions. For example, a split second before you speak, motor cortex sends out two neural signals: a primary neural discharge produces the sound, and the other is a corollary of that discharge that communicates with auditory cortex to prepare it for the sounds you are about to say. However, because of the poor spatial resolution of the EEG and ERP signals, it is possible that activity recorded at the scalp is a combination of the motor command, the corollary discharge, and auditory cortical response to the spoken sound. While these signals are difficult to disentangle with scalp recordings, we have seen N1 suppression in recordings directly from auditory cortex in patients undergoing evaluation for surgical resection of epileptogenic brain tissue⁴⁶.

Whether reflecting the motor command or the corollary discharge, the neural activity *preceding* speech becomes synchronized about 100ms before speech onset, and the amount of pre-speech synchrony is directly related to the degree of auditory cortical suppression

during speech¹⁶. Similar pre-movement changes in neural firing have been shown to index corollary discharge mechanisms in the visual domain in non-human primates⁶. We consider this work to be an example of translational neuroscience, as we are pursuing concepts and methods in humans used by bench neuroscientists.

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Figure 1.

Cartoon illustrating the action of the efference copy/corollary discharge mechanism. The notion to say “ah” is represented as a thought bubble in the speech production areas of the frontal lobe. An efference copy of the motor speech program is then sent from speech production areas in the frontal lobes to auditory cortex. A corollary discharge of the expected “ah” sound is generated in auditory cortex, representing the expected auditory consequences of speech. This is represented as a green burst, overlaid with “ah” in the cartoon. An auditory re-afference is produced by the vocalized speech and represented as an “ah” entering the ear. When auditory re-afference (what you hear) matches the corollary discharge (what you intended to say), auditory cortical responsiveness is suppressed.

Figure 2.

A schematic illustration of the system showing the two computers, the EEG system, the headphones, microphones, subject placement.

Figure 3.

Continuous EEG data from one electrode are plotted in blue. The gray, shaded area shows the $\pm 50\mu\text{V}$ range used for artifact rejection, red lines mark individual “Ah” onset points, and dotted lines mark two blinks in the noisy (top) and clean (bottom) recording examples. The second and third trials in the noisy condition (top) contain high-frequency muscle artifact, while the first trial contains a blink at its onset. In the clean condition (bottom), blinks only precede speech onset and samples are within artifact rejection range. Voltage is on the y-axis and time in milliseconds is on the x-axis.

Figure 4.

Examples of the speech-onset detected by an automated algorithm (vertical red or green line) are shown. B shows the manual adjustment of “ah” trial onset shown in A. When the speech-onset cannot be distinguished from background activity, as in example D, the trial should be excluded from analysis. Other trials, such as example C, have a somewhat ambiguous speech onset (shaded rectangle) and the investigator must decide to adjust the onset or reject the trial from further analysis.

Figure 5.

Single subject ERPs at electrode Cz are plotted from the Talk condition (top) and Listen condition (bottom) before (red) and after (blue) manual inspection and adjustment of speech onset selected by an automated routine. The area shaded in gray marks the N1 component, which has an earlier peak latency and more negative peak amplitude relative to the baseline period after speech-onset adjustment (blue waveforms, top and bottom). Negativity at Cz is plotted down. Voltage is on the y-axis and time in milliseconds is on the x-axis.

Figure 6.

Grand average ERPs recorded during Talk (red lines) and Listen (blue lines) conditions are overlaid. Negativity at Fz, Cz, and Pz is plotted down. Voltage is on the y-axis and time in milliseconds is on the x-axis. We show that N1 is suppressed to speech onset during talking compared to listening.

Troubleshooting Table

Step	Problem	Possible Reason	Solution
Set up (3)	Subject cannot hear her voice.	Microphone level may be low or muted.	Tap the microphone, ask subject if she hears you, plug in/turn on microphone, or check sound control panel to make sure the microphone is not set to "mute".
Recording (4 or 14)	Triggers are not recorded.	Disconnected cable or incorrect recording configuration.	Confirm trigger cable connection from presentation computer's parallel port to EEG system, or load appropriate configuration file in EEG acquisition program.
Recording (5)	Recording is noisy (e.g. Figure 3 Top).	Subject is creating muscle artifacts.	Stop task recording, remind subject how to perform task, and restart task.
Recording (13)	Subject cannot hear playback of her voice.	No speech was recorded.	Check microphone test step, repeat Talk condition recording, and discard previously recorded Talk condition EEG data.