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Can the Lateralized Readiness Potential Detect Suppressed Manual Responses to Pure Tones?

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David Jackson Morris*
K. Jonas Brännström†
Catherine Sabourin‡

Abstract

Background: Willfully not responding to auditory stimuli hampers accurate behavioral measurements. An objective measure of covert manual suppression recorded during response tasks may be useful to assess the veracity of responses to stimuli.

Purpose: To investigate whether the lateralized readiness potential (LRP), an electrophysiological measure of corticomotor response and suppression, may be of use in determining when participants hear but do not respond to pure tones.

Research Design: Within-subject repeated measures with a Go–NoGo paradigm.

Study Sample: Five males and five females (mean age = 38.8 years, standard deviation = 8.8) underwent electrophysiology testing. All had normal hearing, except one.

Intervention: Participants were tested in a condition where they consistently responded to tonal stimuli, and in a condition where intensity cued whether they should respond or not. Scalp-recorded cortical potentials and behavioral responses were recorded, along with a question that probed the perceived effort required to suppress responses to the stimuli.

Data Collection and Analysis: Electrophysiology data were processed with independent component analysis and epoch-based artifact rejection. Averaged group and individual LRPs were calculated.

Results: Group averaged waveforms show that suppressed responses, cued by NoGo stimuli, diverge positively at approximately 300 msec poststimulus, when compared with performed (Go) responses. LRPs were comparable when Go responses were recorded in a separate condition in which participants responded to all stimuli, and when Go and NoGo trials were included in the same condition. The LRP was not observed in one participant.

Conclusions: Subsequent to further investigation, the LRP may prove suitable in assessing the suppression of responses to audiometric stimuli, and, thereby, useful in cases where functional hearing loss is suspected.

Key Words: electrophysiology, functional hearing loss, lateralized readiness potential

Abbreviations: EEG = electroencephalography; LRP = lateralized readiness potential; SD = standard deviation

*Department of Nordic Studies and Linguistics, Audiology and Speech Pathology, University of Copenhagen, Copenhagen, Denmark; †Department of Logopedics, Phoniatrics and Audiology, Clinical Sciences in Lund, Lund University, Lund, Sweden; ‡Ordre des orthophonistes et audiologistes du Québec, Polyclinique de l'Oreille – Audiosanté, Montréal, Canada

Corresponding author: David Jackson Morris, Department of Nordic Studies and Linguistics, Audiology and Speech Pathology, University of Copenhagen, Copenhagen S DK 2300, Denmark; Email: dmorris@hum.ku.dk

INTRODUCTION

To state a platitude, behavioral measures of hearing sensitivity with air- and bone-conducted stimuli are a mainstay of audiological assessment. Suppressing or providing false behavioral responses may result in the reporting of spurious hearing sensitivity. This may involve feigning responses for populations undergoing hearing screening to fulfill occupation-specific sensory criteria, such as pilots and police, where there may be an incentive to provide spurious responses so that they appear to be better than they are. False behavioral responses may also be provided to thwart a clinician. The upshot of this can be a functional hearing loss, that is, an apparent hearing loss that is not attributable to a discernible cause or disorder. Although an important task, detecting and resolving functional hearing loss is unlikely to be pleasant for the clinician and it takes resources from worthier clinical pursuits that may directly benefit other clients.

Functional hearing loss can involve stimulus perception, but conscious and willful suppression of the response by the client. The motivation that lies behind this is variable, but includes the possibility of seeking financial compensation for a nonexistent hearing loss (Gelfand, 2001; Martin, 2014). The incidence rate of functional hearing loss may be minimal among regular audiology caseloads, but it increases in military and medical–legal contexts (Barrs et al, 1994). Some reports have noted higher incidence rates of unilateral than bilateral functional hearing loss, and also that clients can exaggerate so that a functional loss overlays what is later resolved to be a mild or moderate hearing deficit (Gelfand and Silman, 1993; Qiu et al, 1998).

Gelfand and Silman (1993; 1985) examined the relationship between the functional and the resolved, or organic, hearing losses in both unilateral and bilateral cases. They found an inverse relationship between the resolved hearing loss and the functional component whereby larger functional components were accompanied by smaller organic losses and vice versa. This inverse relationship was most apparent in ears where there was a precipitous decrease in the underlying organic loss between adjacent audiometric test frequencies and was attributed to recruitment, which was also demonstrated by Coles and Mason (1984). Furthermore, Gelfand and Silman (1993) suggested that participants use a strategy whereby stimuli are compared with an "internalized loudness-level anchor." According to this strategy, the client responds when the intensity of the stimuli is perceived to be louder than their internal loudness anchor, and they suppress their responses when the stimulus intensity is deemed to be below it. Such a strategy indicates that clients, aiming to feign a hearing loss, are adept at maintaining and suppressing responses when the intensity of the stimuli is either above or below the level anchor. The present study explores the possibility of measuring differences between when participants manually respond or suppress responses to suprathreshold pure-tone audiometric stimuli with the lateralized readiness potential (LRP).

The LRP is a difference waveform that accompanies limb movement and reflects central response activation processes required to perform motor tasks. In bimanual tasks, these processes arise in the motor cortex when the participant knows with which hand she or he is supposed to react (Hagoort and Turennout, 1997; Luck, 2005). Performed responses are mediated via the frontostriatal network and involve motor areas of the brain contralateral to the response hand (Aron and Poldrack, 2006). The precise functional neuroanatomical network involved in the suppression of hand responses is not completely understood, but is thought to predominantly involve ipsilateral brain structures (Aron et al, 2014). In this way, the LRP reflects asymmetrical motor-specific preparation that is not affected by handedness, as it has been recorded from left- and right-handed participants (Kutas and Donchin, 1980). The LRP is commonly recorded from centro-lateral electrodes positioned above the left and right motor cortices, and it is calculated according to a preponderance formula from averaged time series data (de Jong et al, 1988). LRPs associated with performed manual responses deviate negatively in voltage when compared with those associated with suppressed responses that are not executed.

The present study examines whether the LRP difference between performed and suppressed responses may be useful in adult cases where functional hearing loss is suspected. We investigate this by comparing the results of Go trials, where stimuli were presented and a response was given, with NoGo trials for which participants were instructed not to respond when stimuli were presented. Our aim was to evaluate whether the LRP may be useful in differentiating between Go and NoGo trials when cued by intensity changes in pure-tone stimuli. We also compare results from conditions in which Go and NoGo trials are presented in the same and in different blocks, as this has the potential to halve the test time.

METHOD

Participants

Ten participants participated in this experiment, of whom five were identified as female and five as male (mean age = 38.8 years, standard deviation [SD] = 8.8). None of the participants reported a preexisting neurological condition, and all had normal hearing sensitivity as confirmed by pure-tone screening at 20-dB HL for the octave frequencies between 250 and 4000 Hz, and at 6000 Hz. One participant, who is the first author, failed the screening in one ear because of a unilateral moderately severe hearing loss attributable to previously diagnosed otosclerosis. Results from this participant are included as the difference in stimulus intensities was audible to him in both ears, and his LRP results did not differ markedly from other participants.

All participants were apprised of the aims of the study, namely, that in one of the testing conditions, their responses would simulate a hearing loss. They provided their written informed consent before participation, as was stipulated in the approval granted by the Regional Ethics Board in Lund, Sweden, Protocol 2018/359.

Stimuli

The Go–NoGo paradigm was based on 1-kHz pure tones of 0.8 sec duration with a 10-msec linear on and offset ramp. The tones were presented from the stimulus computer with circum-aural Sennheiser (HD 201) headphones. These were calibrated according to ISO 389-8 using a Brüel and Kjaer 2231 sound level meter and a 4134 microphone in a 4153 artificial ear, so that they were 73-dB HL (80-dB SPL) and 79-dB HL (86-dB SPL), respectively. These stimuli were chosen because 1 kHz is a common measurement frequency in audiometry. Also, it was expected that the 6-dB difference in intensity would be perceptible and adequately cue Go–NoGo responses, as this difference corresponds to relative half-loudness judgments, as measured on an interval scale, when the standard was a 1-kHz tone at 85-dB SPL (Warren, 1970).

Electrophysiology

Electroencephalography (EEG) recordings were made with a Neuroscan recording system where the scalp-recorded electrical signal was digitized at 500 Hz. Electrodes were positioned at standard scalp locations for a 32-channel recording, according to the extended international 10–20 system, which included C3 and C4. Skin–electrode impedance values were measured before testing and were under 5 kΩ for all recording channels, the linked mastoid reference sites and four oculogram channels (horizontal and vertical).

Procedure

After the application of the electrodes, participants underwent electrophysiology in two conditions which where (a) respond, including only Go trials, and (b) suppress, including an equal number of Go and NoGo trials. In the respond condition, participants were instructed to respond to all tones by pressing the left or right arrow on a computer keyboard with their left or right index finger, so that the arrow direction corresponded to the ear in which they had heard the tone. In the suppress condition, they were instructed to respond in the same manner to the 79-dB HL tones but not to respond to the softer 73-dB HL stimuli. Responses, or lack thereof, were paired with event synchronization codes and recorded simultaneously with the EEG data. All participants completed the respond block first to gain familiarity with the stimuli and so as to better suppress their responses to the softer 73-dB HL tones in the subsequent condition. An overview of the conditions is given in Table 1.

Stimuli were monaurally presented, and intensity and ear order were quasi-randomized. Both stimulus intensities were presented 150 times to each ear in each condition. The window in which participants could respond, which was also the interstimulus interval, was roved between 1 and 1.4 sec, in order that responses were not rhythmically entrained.

At the completion of EEG testing, participants were asked to indicate the effort that was required to suppress NoGo responses during the final condition according to the Borg-CR10 scale (Borg, 1982; Hua et al, 2014) which is from not at all (0) to extremely strong (10).

Because of changes in the stimulus presentation computer, two participants were tested at intensities which were approximately 8 dB higher than the calibration. However, the relative intensity difference between the stimuli was the same, and as results from these participants did not differ markedly, we opted to use their results.

EEG Processing

Continuous EEG was band-pass filtered (zero-phase) at 0.1–20 Hz and referenced to the linked mastoid electrodes (M1 and M2). It was then visually inspected, and data portions where there was noise across all channels, indicative of participant movement, were deleted. The EEG was then submitted to independent component analysis after which a mean of 2.4 (SD = 0.6) components were removed that were indicative of either ocular movement or noisy electrodes. The oculogram channels were then deleted, and epochs of −200 to 1,000 msec, relative to stimulus onset, were extracted and baselined to the prestimulus data. The epoched data underwent noise reduction so that epochs containing ±100 μV were

Table 1. Summary of Conditions, Stimuli, Trial Type, and Instructions

	Condition	
Intensity	Respond	Suppress
73-dB HL	Go—press key	NoGo—do not press key
79-dB HL	Go—press key	Go—press key

deleted along with epochs where the maximum slope was greater than 0.5 SD/epoch. After artifact rejection, there were 5,330 epochs from the respond condition and 5,590 epochs from the suppress condition.

LRP

To calculate the LRP, we used the canonical double subtraction formula from de Jong et al (1988):

$$\left(C3'(t)_{\mathrm{RIGHT\,HAND}} - C4'(t)_{\mathrm{RIGHT\,HAND}}\right) - \left(C3'(t)_{\mathrm{LEFT\,HAND}} - C4'(t)_{\mathrm{LEFT\,HAND}}\right) \quad (1)$$

where $C3'(t)$ and $C4'(t)$ are the time series data from the centro-lateral electrodes C3 (left) and C4 (right), respectively. The LRP is sometimes displayed as a single-difference curve; however, we provide the averaged responses from both the Go and the NoGo trials.

Software

Stimuli were generated in PRAAT (Boersma and Weenink, 2012) and presented in PsychoPy (Peirce, 2007). Analyses were performed with EEGLAB (Delorme and Makeig, 2004) in the MATLAB environment, and R (Core team R, 2005).

RESULTS

Behavioral

The behavioral responses recorded during EEG testing are given in Table 2 and show consistent responses above 97% in the respond condition. In the suppress condition where participants were instructed to press response keys for the 79-dB but not the 73-dB HL stimuli, the accuracy of responses, when stimuli were presented to the left ear, was considerably less than when it was presented to the right ear.

EEG Suppress–Respond Conditions

Figure 1 shows the group C3/4 electrode data and the LRP differences calculated according to formula 1, for the 73-dB HL stimuli recorded in both respond and suppress conditions. From 200 msec, there is a divergence between the Go and NoGo waveforms. Furthermore, consistent with textbook descriptions of the LRP, there is a brief negative deflection during the NoGo trials between 200 and 325 msec. The mean difference between the Go and the NoGo trials in the temporal window from 200 msec until the end of the epoch is 0.93 μV.

Table 2. Percentage Mean Behavioral Responses Recorded during Both Conditions (SD)

	Condition	
Intensity—Ear	Respond	Suppress
73-dB HL—Right	99.08 (1.36)	4.25 (5.23)
73-dB HL—Left	98.97 (1.71)	34.99 (4.43)
79-dB HL—Right	97.78 (4.25)	94.75 (4.53)
79-dB HL—Left	99.41 (1.46)	65.95 (5.3)

Note: In the suppress condition, participants were instructed to respond to the 79-dB but not the 73-dB HL stimuli.

EEG Suppress Condition

Data from only the suppress condition were analyzed in the same way as the respond-Go and suppress-NoGo comparison, except that the Go responses were from the 79-dB HL stimuli for which participants had been instructed to press the response keys. As the accuracy of left hand/ear responses was poor (see Table 2), we corrected the EEG data by removing epochs from the suppress condition where participants had not responded to the 79-dB HL tones (Go) and responded to the 73-dB HL tones (NoGo). After the left-hand responses were corrected for accuracy, there remained 895 epochs from the 73-dB HL stimuli and 975 epochs from the 79-dB HL stimuli. Figure 2 shows the electrode averages and LRP waveforms from the suppress condition. There is a divergence between the Go and NoGo waveforms between approximately 325 and 1,000 msec, the mean difference of which was 0.98 μV for all epochs and 1.24 μV after the NoGo trials were corrected for accuracy. A pairwise comparison of the individual mean voltages in the 200–1,000 msec poststimulus window showed a difference between the uncorrected Go and NoGo trials [$t_{(9)} = -4.24, p = 0.002$], indicating that there was significant differentiation between the LRP waveforms.

Individual Data

The mean amplitude difference between the Go and NoGo LRP waveforms in the 200–1,000 msec poststimulus window was greatest in the suppress condition, and after artifact rejection, there remained marginally more epochs from this condition. For these reasons, we examined the individual data from the suppress condition, and these are given in Figure 3. It can be seen that the Go waveforms generally diverge negatively from the NoGo waveforms after 200 msec. Table 3 gives the mean difference per individual between waveforms within the 200–1,000 msec poststimulus window and shows that this difference is greater than 0.4 μV, for all participants except S6. S6 was not the participant with hearing loss, and behavioral results obtained from this participant were within 1 SD from the mean, indicating that this participant had responded appropriately and may not have a recordable LRP. S5 and S8 were the participants tested at higher intensities (see "Method" and "Procedure").

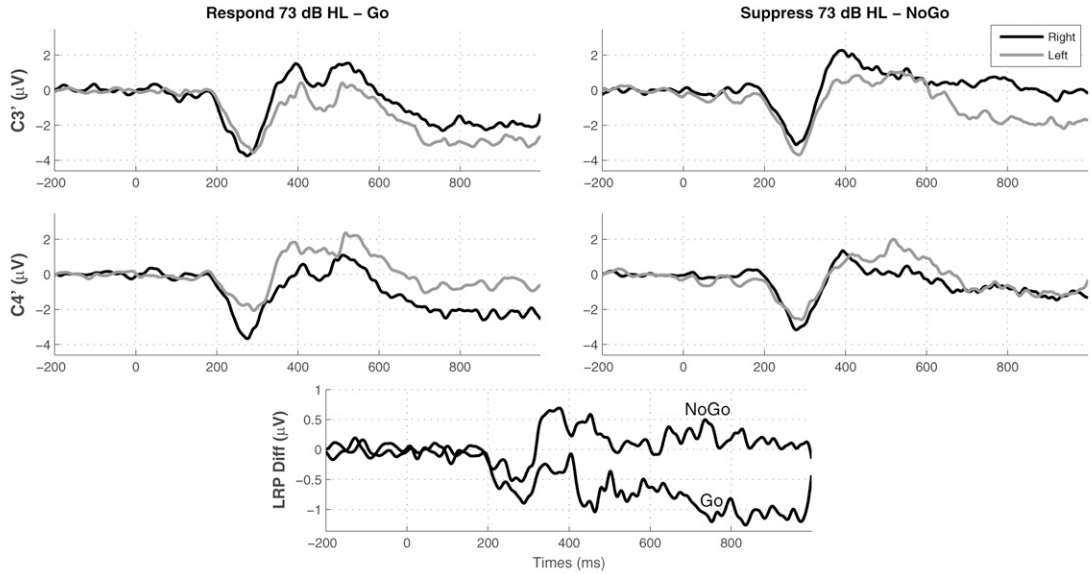

Figure 1. Averaged waveforms from C3 (upper panels) and C4 electrodes (mid panels) recorded from the 73-dB HL stimuli in the respond condition (left panels) and from the 73-dB HL stimuli in the suppress condition (right panels). Right-hand responses to right-ear stimulation (black) and left-hand responses to left-ear stimulation (gray). The lower panel shows the averaged LRP difference waveforms.

Perceived Effort of Suppression

Data from the seven participants who answered the posttest question showed that suppression of responses was perceived as being relatively easy. The mean score corresponded to the answer alternative weak (easy) and was 1.92 (SD = 1.09). We compared the mean voltage difference in the 200- to 1,000-msec poststimulus window with the perceived effort exerted in suppressing responses, but these measures were not correlated ($\rho = 0.54$, $S = 25.61$, $p = 0.21$).

DISCUSSION

In the suppress condition of this study, we instructed participants not to respond to the 73-dB HL tonal stimuli, which were NoGo trials, to simulate when a patient hears audiometric stimuli but chooses not to respond. The resultant NoGo LRP difference waveform diverged from that obtained from Go trials, where participants responded when the intensity of the auditory stimuli was the same in a separate respond condition and also when Go trials were recorded from stimuli that

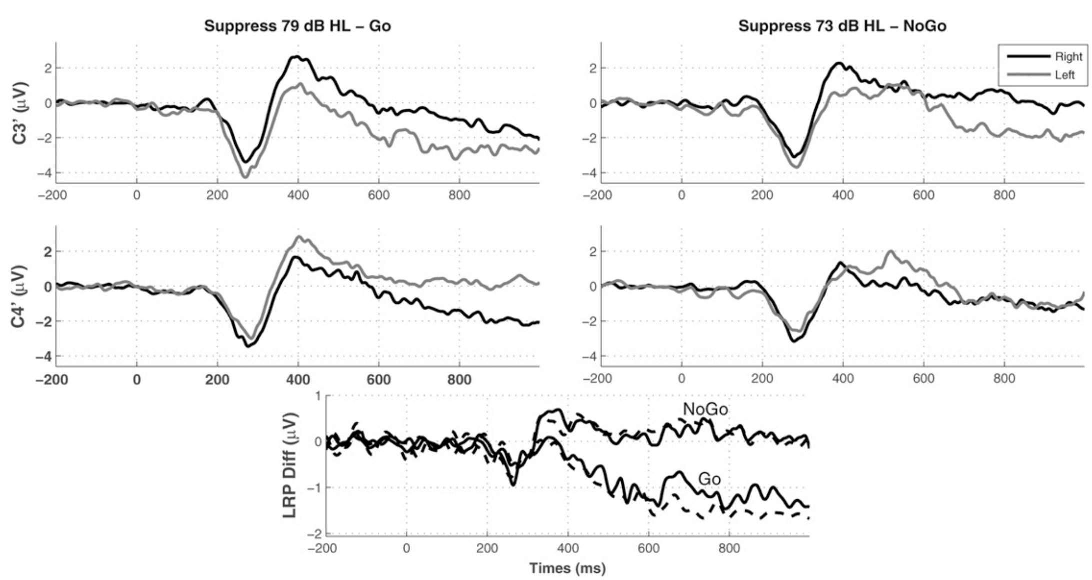

Figure 2. Averaged waveforms from C3 (upper panels) and C4 electrodes (mid panels) recorded from the 79-dB HL stimuli (left panels) and from the 73-dB HL stimuli (right panels), both recorded in the suppress condition. Right-hand responses to right-ear stimulation (black) and left-hand responses to left-ear stimulation (gray). The lower panel shows the averaged LRP difference waveforms for the Go and NoGo trials (solid), and also after they were corrected for accuracy (dashed).

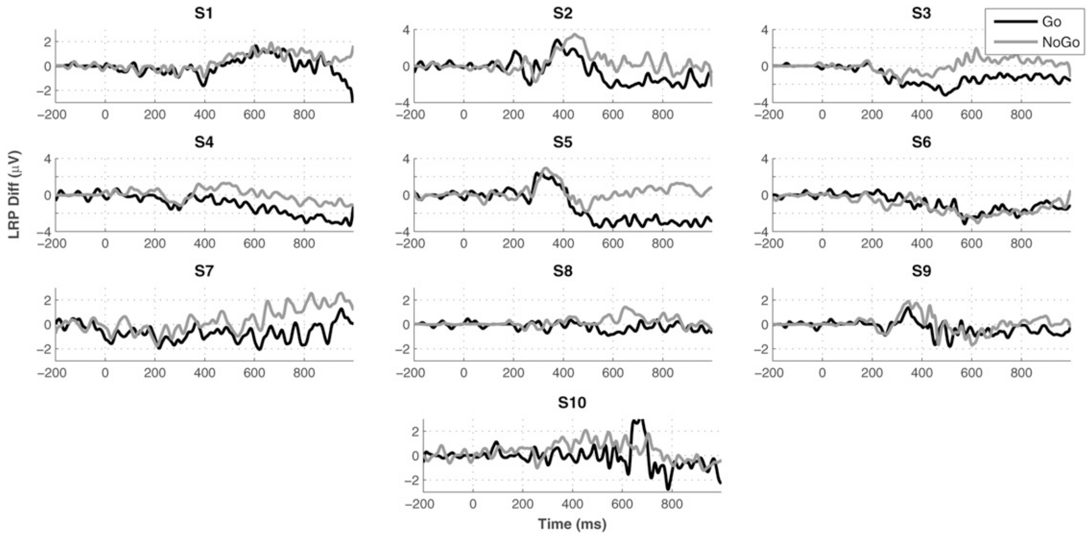

Figure 3. LRP waveforms from individual participants recorded with the 79-dB HL stimuli (Go—black) and 73-dB HL stimuli (NoGo—gray), both from the suppress condition. Note that the *y*-axes of S2 to S6 are scaled differently.

were 6 dB greater in intensity within the same condition. This finding corresponds with the view that the double subtraction formula (1) cancels out ERP components and, thus, stimulus differences are of little consequence to the LRP (Luck, 2005). Mean measurements of the voltage difference between Go and NoGo trials in the 200–1,000 msec poststimulus window suggest that one of the ten participants did not have a recordable LRP, which serves as some indication of the viability of the measurement.

In the behavioral data recorded during the suppress condition, we observed that the mean response accuracy for tones presented to the left ear was approximately 30% lower than for those presented to the right ear (see Table 2). This observation suggests that there is a difference in either perceptual acuity or manual dexterity between ears and hands that affects responses to auditory stimuli. This asymmetry also suggests that a practiced functional hearing loss client may favor their right ear when simulating a hearing loss. This in turn suggests that in cases of suspected functional hearing loss, consideration could be given to pursuing a behavioral strategy whereby participants respond with the response switch in their nondominant hand.

Group mean data from left-hand responses at electrode C4 to NoGo trials show a bifid waveform with peaks at approximately 400 and 500 msec (see Figures 1 and 2). This is unlikely to be related to the poorer accuracy of left manual responses, as waveforms from C3 and C4 to Go responses in the respond condition, where accuracy was high, show the same approximate shape at similar poststimulus latencies (see Figure 1). This suggests that some other process, possibly arising from a nonmotor area of the brain (Eimer, 1998), may have contributed to this central scalp-recorded activity.

Common objective measures that are used to resolve suspected functional hearing loss are acoustic reflexes, auditory brain stem responses, otoacoustic emissions, and middle and late latency responses (Coles and Mason, 1984; Barrs et al, 1994; Lin and Staecker, 2006; Dobie, 2015). In short, these methods all have their innate sensitivity, advantages, and pitfalls. The LRP may complement these techniques, as it is an objective measure that is sustained over a broad poststimulus temporal window. This is in contrast to other electrophysiology measures, such as event-related potential components that generally peak at certain electrode sites within specific poststimulus latencies. Although the LRP may be measured in tandem with other psychophysical-based routines such as the Stenger test, it seems to be most suitable for suspicious bilateral hearing loss cases. A disadvantage that may limit possible utilization of the LRP is the measurement time that it requires. In the present study, the suppress condition, involving one test frequency, took approximately 25 min and varied slightly depending on the response speed of the participant. This is considerably longer than the test time involved in

Table 3. Individual Participant Differences between the Go and NoGo Waveforms from the 200 to 1,000 msec Poststimulus Window from the Suppress Condition

	S1	S2	S3	S4	S5	S6	S7	S8	S9	S10
Mean LRP difference (μV)	0.504	1.321	1.431	1.638	2.225	−0.235	1.412	0.499	0.425	0.633

hearing threshold estimation using N1–P2 responses to tonebursts, which has been reported as being as low as 5 min (Van Maanen and Stapells, 2005) and even 3½ min per test frequency (Lightfoot and Kennedy, 2006). Also, and unlike auditory N1–P2 responses to tonebursts, the LRP is not a measure that is directly linked to perception, but is instead a measure of response preparation from the motor cortex. This could also be considered as a positive attribute, as the response from the motor cortex implies that antecedent auditory sensory processing has been accomplished.

Although the present small-scale investigation shows that the LRP is a viable objective measure, there are further issues to be explored in relation to its potential adoption in resolving functional hearing loss. These include the differentiation of NoGo responses from stimuli that are genuinely not perceived, that is, true negatives. The negative voltage deflection observed in the group NoGo responses between 200 and 325 msec (see Figures 1 and 2) may prove to be of use in differentiating these, as it is likely to be absent in stimuli that are not perceived. It would also be worthwhile to investigate how the LRP is affected by a difference in haptics when recorded with audiometric response switches and also with auditory stimuli that are close to the hearing threshold. For technical reasons, thumb-depressed response switches were not used in the present study and neither were near-threshold stimuli, as we were interested in cueing unequivocal Go and NoGo responses. Although the LRP is primarily a motor cortical response and should not be affected by stimulus attributes, such as intensity changes, variation of task difficulty does modulate the LRP with larger effects for simpler tasks (van der Lubbe et al, 2001). Furthermore, it may be worthwhile to vary the time limits under which responses can be made as speed–accuracy tradeoffs can influence the time course of the LRP (Rinkenauer et al, 2004) and may prove useful in thwarting the response strategy of a malingerer.

In summary, we report that the LRP could be recorded within one block of testing where participants responded to Go trials and suppressed manual responses to NoGo trials, when both were cued by an intensity difference in pure-tone stimuli. Mean differences between the LRP waveforms from suppressed and performed manual responses were in the order of 1 μV in the 200–1,000 msec poststimulus window. These results suggest that the LRP may be useful as an adjunct measure in resolving functional hearing loss, particularly with persistent feigners who have attained consistency in providing spurious behavioral responses to pure tones.

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