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Auditory brainstem responses obtained with randomised stimulation level

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Abstract

Objective: To present randomised stimulation level (RSL) – a stimulation paradigm in which the level of the stimuli is randomised, rather than presented sequentially as in the conventional paradigm.

Design: The value of RSL was evaluated by (i) comparing the morphology of auditory brainstem responses (ABRs) elicited by the conventional and RSL paradigms, and by (ii) an online survey investigating the hearing comfort of the stimulus sequence.

Study sample: ABRs were obtained from 11 normal-hearing adults (8 females, 25–29 years). The online survey was administered to 238 adults from the general community.

Results: Results showed that (i) both stimulation paradigms elicit ABR signals of similar morphology, (ii) RSL provides a faster comprehensive representation of the ABR session, and that (iii) the general population found RSL stimuli to be more comfortable.

Conclusions: The simultaneous evaluation of all ABR traces of the session provided by RSL has potential to improve the identification of ABR components by enabling clinicians to make use of the *response tracking* strategy from the start of the test, which is critical in situations where ABRs present an abnormal morphology. New research opportunities and the clinical potential of RSL are discussed.

Keywords

Response tracking; response detection; hearing comfort; test time.

1. Introduction

The auditory brainstem response (ABR) is a widely used auditory evoked potential in a broad range of clinical applications (Burkard and Don, 2007). ABRs are conventionally elicited by sequences of periodic stimuli such as clicks or tone bursts presented at a fixed level (Ferm et al., 2013; Stevens et al. 2013; Stürzebecher et al. 2001), and it is a common practice to stop presenting auditory stimuli when the experienced audiologist or clinician determines that a neural response is present on the averaged waveform (Hall, 2007; Sininger, 2007).

Three methods are typically used for subjective (visual) response detection: (i) *response judgement* – which relies on the tester's experience to determine if the response components are present based on peaks having reasonable amplitudes and occurring at plausible latencies; (ii) *response replication* – in which the tester judges if two or more ABR waveforms obtained by splitting the available sweeps sufficiently replicate in time and magnitude (higher replication indicating higher confidence in claiming the presence of neural activity); and (iii) *response tracking* – in which the main components of the ABR can be identified by tracking the expected changes on the morphology as a function of a stimulus parameter, e.g. amplitudes decrease and latencies increase as level decreases (Elberling and Don, 2007).

Tracking the ABR components as a function of the stimulus level can be of particular interest to visually determine the presence of a neurophysiological response in complex scenarios where the ABR morphology diverges from standard patterns, such as (i) in individuals with hearing loss (whose ABR components are delayed and present a smaller amplitude) (Hall, 2007; Sininger, 2007); (ii) in individuals with auditory central nervous system disorders, including acoustic neuroma (where ABRs present prolonged waves I-V interpeak latencies compared to the normal-appearing ABR) (Naito et al., 1999) and auditory neuropathy spectrum disorder (present cochlear microphonics but absent or severely abnormal ABRs) (Hood, 2007); or (iii) when ABRs are elicited by an electrical stimulus (where ABRs are substantially distorted by the electrical artefact and the latency of their components is shorter) (Hey et al., 2007).

The main drawback of current practice is that experienced audiologists and clinicians need to wait until several ABR traces are available to benefit from the *response tracking* strategy. For this reason, this study aimed to investigate the value of randomised stimulation level (RSL) – a stimulation paradigm that enables the simultaneous visualisation of ABR waveforms elicited by different stimulus levels from the start of the test, aimed at providing a faster comprehensive representation of the ABR test session.

The advantages of the simultaneous evaluation of various intensities have been discussed in previous studies using *chained stimuli* (Hamill et al. 1991, 1992) – a technique that uses bursts of clicks presented in either ascending or descending levels at a fixed presentation rate. Hamill et al. (1991, 1992) demonstrated that this type of presentation facilitated the visual identification of the ABR components and accelerated the estimation of the hearing threshold. While the stimulation paradigm proposed in this study presents some similarities with the chained-stimuli technique, it differs in that both the presentation level of the stimulus and the presentation rate are randomised.

The present study also evaluated the hearing comfort of the proposed stimulation strategy. Hearing comfort is a critical variable for the success of the test session, particularly in newborns and infants, since hearing discomfort may prevent them from remaining quiet and still during the test (Diefendorf, 2014). In most instances, the auditory stimulus is found unpleasant when abrupt changes of sound are presented (e.g. the sudden presentation of a high sound level) (Pitchforth, 2010); however, the continuous presentation of a particular auditory stimulus pattern is easier to inhibit due to two mechanisms: (i) *neural adaptation* – a decrease in the activity pattern when a continuous stimulus is presented (Thornton and Coleman, 1975; Gillespie and Muller, 2009); and (ii) *habituation* – a cognitive process associated with selective attention which enables filtering out non-essential stimuli by decreasing the response to a stimulus after prolonged presentations of that stimulus (Rankin et al., 2009; Thompson, 2009). Since the proposed stimulus paradigm consists of a stimulus pattern repeated all along the test session, we predicted that this auditory stimulus would be easier to inhibit, and that the general population would report higher levels of hearing comfort. Furthermore, we also anticipated that due to the adaptation and habituation mechanisms described in the literature, RSL and the conventional paradigm would elicit auditory evoked potentials of different morphology.

2. Materials and methods

2.1. Electrophysiology

Subjects & Ethics. Eleven young adults (8 females, aged 25-29 years) met the inclusion criteria of reporting no significant hearing difficulties and absence of a history of auditory dysfunction, and volunteered to participate in the study. The test protocol was in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) for experiments involving humans and was approved by the Ethics Committee of the University of Granada (Ref. no. 961/CEIH/2019).

Auditory stimulus. The auditory stimulus consisted of 100 µs rarefaction clicks presented with an inter-stimulus interval (ISI) that varied randomly between 38–48 ms following a uniform distribution, i.e. with an average stimulation rate of 23.26 stim/sec. The auditory stimulus was presented monaurally in the right ear via insert earphones (3M E-A-RTONE 3A, 3M Company Inc., St Paul, MN) at four stimulus levels, i.e. 80-60-40-20 dB normal hearing level (nHL). The 0 dB nHL reference level was estimated as the mean level of the hearing threshold estimated in 10 adults (5 female, 23–38 years) without a history of any hearing dysfunction, and with audiometric pure-tone thresholds equal or below to 10 dB in octave band 0.5–8 kHz frequencies in both ears. The test time dedicated to each stimulus level increased as level decreased in order to compensate for the loss of signal-to-noise ratio (SNR) due to the lower-amplitude components at lower levels, being 153.6 s (around 3,500 stimuli) at 80 dB nHL, 211.2 s (around 4,900 stimuli) at 60 dB nHL, 268.8 s (around 6,250 stimuli) at 40 dB nHL, and 326.4 s (around 7,600 stimuli) at 20 dB nHL. Two stimulus paradigms were used, both with a test time duration equal to 16 minutes:

a. *Conventional stimulation*: The four levels were presented sequentially in descending order, i.e. 80 dB nHL, followed by 60 dB nHL, 40 dB nHL, and 20 dB nHL. This stimulation paradigm recreates the current clinical practice for ABR testing.
b. *Randomised stimulation level (RSL)*: The stimuli from the four level conditions (i.e. around 22,250 stimuli in total) were mixed to form a unique stimulation signal in which the stimulus level was randomised.

EEG acquisition. EEG data acquisition took place at the University of Granada (Spain), in a test booth prepared to attenuate acoustical and electromagnetic interference. During the test session, participants were seated in a comfortable couch and were asked to refrain from making abrupt movements and to leave their neck and shoulder muscles relaxed in order to minimize electromyogenic noise. The EEG was recorded by three Ag/AgCl disposable self-adhesive pre-gelled electrodes with offset press-stud connections, placed on the skin at the high forehead (Fz, active), the right mastoid (M2, reference) – ipsilateral to the auditory stimulus, and the low forehead (Fpz, ground). Inter-electrode impedances were kept below 5 kΩ in all recordings. The differential voltage signal between the active and reference electrodes was amplified and band-pass filtered (100–3000 Hz) using a flexible amplifier based on a previous design (Valderrama et al., 2014a), sampled at 20 kHz and stored using 16 bits/sample.

Data analysis. Data processing was carried out using custom-made scripts implemented in MATLAB (The Mathworks, Inc., Natick, MA). The ABR signals were obtained in each test condition by (i) digitally filtering the raw EEG (4^{th} order Butterworth, [100–3000] Hz); (ii) segmenting the filtered EEG into 40 ms sweeps; (iii) rejecting the 25% of the sweeps with higher energy value from the analysis; and (iv) averaging the accepted sweeps. The time delay corresponding to the plastic tube of the insert earphones and the group delay of the analogue and digital filters was compensated.

The morphology of the ABR signals was characterised in terms of the amplitude and latency of waves I, III, and V. The amplitude and latency of the ABR components were measured via a custom-made MATLAB script which presented the four ABR waveforms obtained at different levels, per subject and stimulus paradigm (i.e. RSL or conventional). The presentation order was randomised, and the information of the subject and the stimulus paradigm was not presented to the experienced evaluator to avoid any possible subjective bias. The evaluator was asked to mark the peaks and following troughs of the waves I, III and V that could be identified. Amplitudes were measured as the voltage difference between the peak and the trough; and latencies were measured as the time difference from the peak to the stimulus onset.

The quality of the ABR waveforms obtained with the conventional and RSL stimulus paradigms was compared in terms of their SNR, estimated as the ratio between the variance of the ABR waveform and the variance of the noise, in the [1.0-11.00] ms latency interval. The respective variances were estimated from the conventional average for the ABR waveform, and from the "plus-minus reference" (average obtained by adding half of the epochs and subtracting the other half) for the noise, as proposed by Schimmel (1967). In our implementation, the "plus-minus reference" was estimated using the first-half and the second-half of the available epochs. An overall SNR score was obtained per individual and stimulation paradigm by averaging the SNRs of the four stimulus levels in the linear scale and then converting the average into decibels.

2.2. Hearing comfort survey

Two hundred and thirty-eight adults volunteered to participate in an online survey asking about their preference in terms of hearing comfort between the conventional and the RSL paradigms. In this survey, participants had the opportunity to listen to the two stimulus paradigms for a brief period of time (around 1 minute) and were asked to rate their preference in a 1 to 5 scale (1. Clearly conventional; 2. Conventional; 3. Undecided; 4. RSL; 5. Clearly RSL) considering that the typical duration of these stimulus paradigms is around 20 minutes. In this survey, RSL was compared to the conventional paradigm both in ascending and descending levels. Before rating their preference, participants were asked to adjust the sound level of their devices in a way that (i) a 20 dB nHL click sequence could be barely detected and (ii) three digits presented at 20 dB nHL could be understood, in an attempt to make the presentation level uniform across participants and provide them with an appropriate representation of the hearing experience of a real test. This online survey is presented as supplementary material in Appendix A (Section 1), in which the different stimulation techniques can be heard.

3. Results

3.1. ABR morphology

[Figure 1], [Table 1], [Table 2]

Figure 1 shows the individual ABR signals obtained with the conventional and RSL stimulus paradigms at different hearing levels. This figure shows the expected amplitude reduction and latency increase of the components as the stimulus level decreases. The visual inspection of these figures also shows that the waveform morphology obtained with the two stimulus paradigms is very similar, with the only exception of subject 9, where a strong post-auricular-muscle component (PAM) is observed with the conventional procedure which is absent in the RSL procedure. Minor differences can also be observed in subjects 3, 4 and 7 at latencies 10–12 ms at high stimulation levels.

Table 1 presents the mean and standard deviation of the amplitude and latency of waves I, III and V. The three components could be identified in all participants at all levels. Amplitudes and latencies were consistent with previous literature (Chalak et al., 2013). Two-way repeated-measures analyses of variance showed no statistically significant differences (i.e. p-values > 0.05) between the two stimulation paradigms both for latencies and amplitudes.

Table 2 compares the quality of the ABR waveforms obtained with the conventional and RSL paradigms in terms of their SNR in each participant (rows 2 to 13) and across levels (rows 14 to 18). This table shows that, on average, the quality of the ABR waveforms obtained with RSL is 2.9 dB greater than the ones obtained with the conventional paradigm, even though the statistical significance of this finding is weak (p-value=0.084), probably due to the sample size or the inter-subject variability. This table also shows that the SNR improvement is not uniform across participants, with the highest improvement associated with the participant presenting PAM in the conventional paradigm (i.e. subject 9). Should subject 9 be considered an outlier, its exclusion from the SNR analysis results on an average SNR of +13.54 dB in RSL and +11.15 dB in the conventional mode, i.e. the improvement is reduced to 2.39 dB (p-value=0.29), which supports a strong inter-subject variability in the SNR improvement. The last rows of Table 2 also show that the SNR is not uniform across stimulation levels. A linear regression analysis of the SNR as a function of level showed a statistically significant positive trend between the two variables in the two methods: RSL [r=0.52, y-intercept=3.82±1.89, slope=0.131±0.034, p-value=$3.1\cdot10^{-4}$], conventional [r=0.39, y-intercept=5.45±1.46, slope=0.070±0.027, p-value=$9.6\cdot10^{-3}$]. This trend was expected due to the amplitude increase of the ABR components as level increases (Burkard and Don, 2007). Finally, the last rows of Table 2 also show that the SNR improvement increases with the stimulation level. This is consistent with the increase in the slope observed in the regression analysis of the RSL data with respect to that in the conventional method (even though the difference is not significant, p-value=0.156, probably due to inter-subject variability). A paired Student's t-test (comparing the SNR of both paradigms) separated by stimulation levels provides p-values 0.056, 0.50, 0.29 and 0.86, for stimulation levels at 80, 60, 40 and 20 dB, respectively, showing that the improvement is close to significant (in spite of the small number of observations, only 11) only at the highest stimulation level. The raw data of the SNR per subject and level is presented as supplementary material in Appendix A (Section 2).

3.2. Comprehensive representation of the test session

[Figure 2]

The rapidness in which the RSL and the conventional methods provided a comprehensive representation of the ABR traces of the test session could be subjectively evaluated via a series of videos that re-created the recording of the ABR signals with the two stimulation paradigms.

Despite the total duration of the ABR test session was 960 seconds per method, in order to optimise the visual comparison between the two methods, the videos re-created the ABR waveforms obtained during the first 90 seconds at each level in the conventional mode (i.e. 360 seconds in total), using an equal number of stimuli in RSL for a fair comparison between the two methods. These videos were presented with the conventional mode both in ascending and descending level, and were accelerated in a factor of 10 – thus 360 seconds of recording in real life were presented in 36 seconds in the simulation. These videos are available in the supplementary materials (Appendix B).

Figure 2 shows a series of snapshots of the video that re-creates the ABR recording process with the RSL (left column) and the conventional (right column) techniques for a representative subject of the study (i.e. subject 1) at different time intervals, with the conventional mode presented in descending level. Equivalent snapshots for the remaining participants with the conventional mode both in ascending and descending level can be found in Appendix A (Section 3) of the supplementary materials. The blue lines represent the averaging of all the available responses while the orange lines represent the averaging of the two halves of the available responses. These figures visually demonstrate that early access to all the ABR traces of the session enabled by RSL provides a faster comprehensive representation of the ABR components of the test session. For example, Figure 2 shows that after 180 seconds of testing (third row), the ABR components can be visually identified at all levels in the RSL technique, but at that time, only ABRs at 80 and 60 dB nHL have been recorded with the conventional mode. When the conventional technique is presented in ascending level (see figure 12 in Appendix A), the ABRs obtained with the conventional mode after 180 seconds of testing present an oscillation at the 6–9 ms latencies at 20 and 40 dB nHL which, presented without the remaining higher levels, would be dubious to be determined as ABR components. However, the early access to all the ABR traces of the session provided by RSL enables the visual tracking of the ABR components, thus increasing the certainty of ABR components identification and the detection of a neurophysiological response.

3.3. Hearing comfort

[Figure 3]

Figure 3 presents the results of the online survey investigating the hearing comfort of the conventional and RSL paradigms, both with the conventional paradigm presented in ascending-level and descending-level order. Results show that, irrespective of the order in the conventional paradigm, most participants reported higher levels of hearing comfort with the RSL paradigm. In addition, this figure shows a different satisfaction pattern when RSL was compared to the conventional paradigm in ascending-level or descending-level order, with more participants preferring the conventional paradigm when the level was presented in descending order compared to ascending order.

4. Discussion

This paper presents RSL – a stimulation paradigm in which the level of the auditory stimuli is randomised, rather than presented in sequential order. RSL and the conventional stimulation paradigms were compared in terms of (i) their morphology via a statistical analysis of the amplitude, latency, and SNR; (ii) their subjective rapidness for providing a reliable comprehensive representation of the ABR test session via a series of videos and snapshots re-creating the ABR recording process; and (iii) the hearing comfort of their auditory stimulus via an online survey.

Contrary to our prediction, the statistical analysis of the ABR components showed similar amplitudes and latencies between the two stimulation paradigms (see Section 3.1), which indicates that the neural adaptation mechanisms associated to changes in stimulus level were not significant at the stimulus presentation rate used in this study (i.e. 23.26 stim/sec on average, with ISIs uniformly distributed between 38–46 ms). This outcome is consistent with previous literature, which has shown that neural adaptation mostly influences the ABR morphology at presentation rates above 40 stim/sec (Thornton and Slaven, 1993; Valderrama et al., 2012, Valderrama et al., 2014c). Future studies could investigate the effect of RSL on the morphology of later components (e.g. middle-latency responses or cortical auditory evoked potentials), which are expected to be influenced not only by stronger effects of neural adaptation (Bardy et al., 2014; Valderrama et al., 2014c) but also by habituation (Rankin et al., 2009; Thompson, 2009).

This study also revealed that the average quality of the ABR traces obtained with RSL was around 3 dB higher than the ones obtained with the conventional paradigm. Even though the statistical significance of this improvement was marginal, the experimental results showed that it was more relevant at high stimulation levels. Since the ABR waveforms provided by both paradigms are similar, the SNR improvement of RSL with respect to the conventional paradigm is associated to an increase of the background noise in the last one, specifically concentrated at the highest stimulation levels. The SNR analysis further showed that the SNR improvement was not uniform across participants, and that the greatest SNR improvement was found on the participant who presented a strong PAM myogenic response at high levels in the conventional paradigm, but not in RSL (i.e. subject 9). This result could be associated with the higher hearing comfort of the auditory stimuli of the RSL paradigm, since the PAM component tends to be present in individuals whose neck and shoulder muscles are tense (Hall, 2007; Matas et al., 2009). Future research could investigate the link between hearing comfort and PAM, and whether RSL could lead to AEPs less contaminated by this myogenic response. In this regard, an important advantage of RSL over the conventional method is that the adverse effects of noise and patient state during the test session are distributed equally along the different evaluated levels, which may lead to ABR signals of similar quality across levels.

The videos re-creating the ABR recording process by the RSL and conventional methods visually showed that RSL was more effective in providing a comprehensive representation of all the ABR signals of the test session, which could help audiologists and clinicians make use of the *response tracking* strategy, and increase their confidence in determining the presence of a neurophysiological response and the identification of the ABR components. This is particularly critical in clinical applications that require certainty in the determination of a neurophysiological response and ABRs present an abnormal morphology, such as in cases of cochlear implantation in common cavity deformity (Zhang et al., 2017; Kaga et al., 2020), in patients with an acoustic neuroma (Gordon and Cohen, 1995; Schmidt et al., 2001), or in cochlear-implanted children with an incomplete maturation of their auditory system (Thai-Van et al., 2007). Furthermore, audiologists and clinicians may benefit from accessing all the ABR traces of the session from the start of the test in routine clinical assessments such as hearing threshold estimation. While the re-creations presented in this paper provide a subjective evaluation of the RSL efficiency, new research could investigate the magnitude of the test-time reduction provided by RSL compared to the conventional paradigm systematically in real clinical settings – where audiologists and clinicians decide to stop presenting auditory stimuli when a neural response is detected by visual inspection, in a population with and without hearing impairment.

The similar morphology of ABR signals in terms of amplitudes and latencies between the two stimulation paradigms found in the present work, along with the strong potential of RSL to improve response detection, is consistent with previous studies that have investigated the efficacy of a similar technique that uses bursts of clicks of different levels presented sequentially in ascending or descending order with a fixed stimulation rate – also providing a simultaneous ABR representation across different intensities. This technique was originally proposed by Spoor et al. (1974) for rapid electrocochleography testing, and was later adapted by Hamill et al. (1991,1992) for ABR threshold estimation, who termed this technique as 'chained-stimuli'. These studies showed that when the chained-stimuli technique was compared to the conventional stimulation method, auditory evoked potentials were of similar morphology and the hearing threshold could be determined faster (Spoor et al., 1974; Hamill et al., 1991,1992). Compared to the chained-stimuli method, the proposed RSL technique presents three important advantages that are discussed below.

Firstly, the auditory stimuli in the chained-stimuli method are presented with a fixed presentation rate, however RSL not only randomises the level of the stimuli but also their inter-stimulus interval. This randomisation in the stimulus rate enables the recording of ABRs at rates faster than 100 stim/sec, i.e. using inter-stimulus intervals shorter than the 10 ms averaging window and estimating the transient ABRs via deconvolution (de la Torre et al., 2019, 2020; Valderrama et al., 2012, 2014c). This would allow the investigation of neural adaptation effects derived from both the stimulus presentation rate and level. In fact, Valderrama et al. (2014b) designed an experimental paradigm that enabled the characterisation of two different neural adaptation mechanisms associated with the stimulus presentation rate – this study found that the ABR morphology was affected by both *fast* adaptation (i.e. by the average stimulus presentation rate in the preceding few milliseconds) and *slow* adaptation (i.e. average stimulus rate in the preceding tens of milliseconds). Investigating fast and slow neural adaptation effects derived from both a randomised stimulus rate and level could have important implications in adjacent fields of hearing research, such as the investigation of neural indicators for *hidden hearing loss (HHL* – individuals with audiometric thresholds within the normal-hearing range who present abnormal speech-in-noise intelligibility difficulties) since animal studies have shown HHL to be associated with the inability of midbrain neurons to adapt to loud sound environments (Bakay et al., 2018).

Second, the chained-stimuli method uses bursts of stimuli in either ascending or descending level with a time separation in between bursts. Consequently, the ABRs obtained with the chained-stimuli method will be significantly affected by short-term adaptation (i.e. ABRs morphology will be highly influenced by the immediately preceding stimulus), since the use of the same sequence all along the test will produce a systematic effect on the morphology of each ABR. It can be expected that the effect of short-term adaptation will be of larger magnitude as the stimulus rate increases (Thornton and Slaven, 1993; Valderrama et al., 2012; Valderrama et al., 2014c), which would explain why Hamill et al. (1992) found statistically significant differences in wave V amplitudes between the conventional and the chained-stimuli methods when they were compared in simulated conductive loss participants using a fast presentation rate (i.e. 73 stim/sec), but found no differences when the two methods were compared in a hearing-loss group at a slow presentation rate (i.e. 21.7 stim/sec). In contrast, the RSL technique uses a continuous series of stimuli in which the presentation level is fully randomised, which makes long-term effects of adaptation (i.e. ABRs morphology influenced by the overall presentation rate of several previous stimuli) more prominent. The study of long-term effects of adaptation could have important implications in the study of neurophysiological responses evoked by the fine structure of ecologically valid stimuli such as real speech, in which the level fluctuates significantly in time.

Last, the fact that the chained-stimuli technique uses the same burst of stimuli repeated all along the test implies that the number of presentations per level is constant, i.e. ABRs at different levels are obtained with the same number of stimuli. In contrast, RSL can use stimulation sequences with different number of repetitions per level aimed at compensating the loss of quality due to lower amplitudes at low levels with an increased number of repetitions. For example, this study used around 3,500 stimuli at 80 dB nHL, 4,900 stimuli at 60 dB nHL, around 6,250 stimuli at 40 dB nHL, and around 7,600 stimuli at 20 dB nHL. Moreover, RSL has a strong potential to be further developed – the flexibility of RSL stimulation could enable an optimised selection of the presentation level in real time by considering automatic assessments of the ABRs quality and response detection (e.g. Valderrama et al, 2014d). In addition, RSL could also use auditory stimuli with frequency specificity such as windowed tones in order to simultaneously obtain ABRs evoked by different frequencies – an approach that has been proven valuable using the chained-stimuli method (Mitchell et al., 1999; Petoe et al., 2009).

Results from the online survey evaluating the hearing comfort of both stimulation paradigms showed a higher preference towards the RSL stimuli. Although this trend was not uniform across participants, and some respondents showed a clear preference towards the conventional stimulation, the overall higher satisfaction score of the RSL stimulus is probably associated with a higher facility to inhibit the stimulus. Compared to the conventional stimulation paradigm, which leads to abrupt changes of sounds when different levels are presented, results suggest that the continuous presentation of an auditory pattern in RSL all along the duration of the test may benefit both from neural adaptation (Thornton and Coleman, 1975; Gillespie and Muller, 2009) and habituation (Rankin et al. 2009; Thompson, 2009) mechanisms. It is noteworthy mentioning that the present study evaluated the hearing comfort from the RSL and conventional stimulation paradigms in adults, however from a clinical perspective, it would be highly relevant to conduct new research investigating the hearing comfort of RSL in newborns and infants (i.e. the population in which hearing comfort is critical) (Diefendorf, 2014), and whether RSL leads to lower number of cases requiring light sedation or anaesthesia. It is also advisable to interpret the results of this survey with certain degree of caution, since ratings were not obtained from a realistic testing scenario, but from an artificially accelerated simulation (i.e. 20 minutes of real testing were re-created in a 1-minute survey). Future studies could compare the hearing experience scores reported in this study with the ones obtained in a real clinical setting.

5. Conclusion

This study aimed to investigate the value of RSL – a stimulation paradigm in which the level of the auditory stimuli is randomized, rather than presented sequentially. Results showed that (i) being able to use the *response tracking* strategy from the start of the test facilitates the detection of a neurophysiological response and the identification of the ABR components, (ii) when an average stimulation rate of 23.26 stim/sec was used, the ABR waveforms elicited by the RSL and conventional paradigms presented a similar morphology, and (iii) the general population found the continuous presentation of the RSL stimulus pattern more comfortable compared to the conventional paradigm. These findings support the clinical potential of RSL, and are likely to inspire new research in this domain of hearing research.

Conflict of interest

None of the authors have potential conflicts of interest to be disclosed.

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Supplementary material

Supplementary materials associated with this article can be found at http://10.1080/14992027.2022.2047233.

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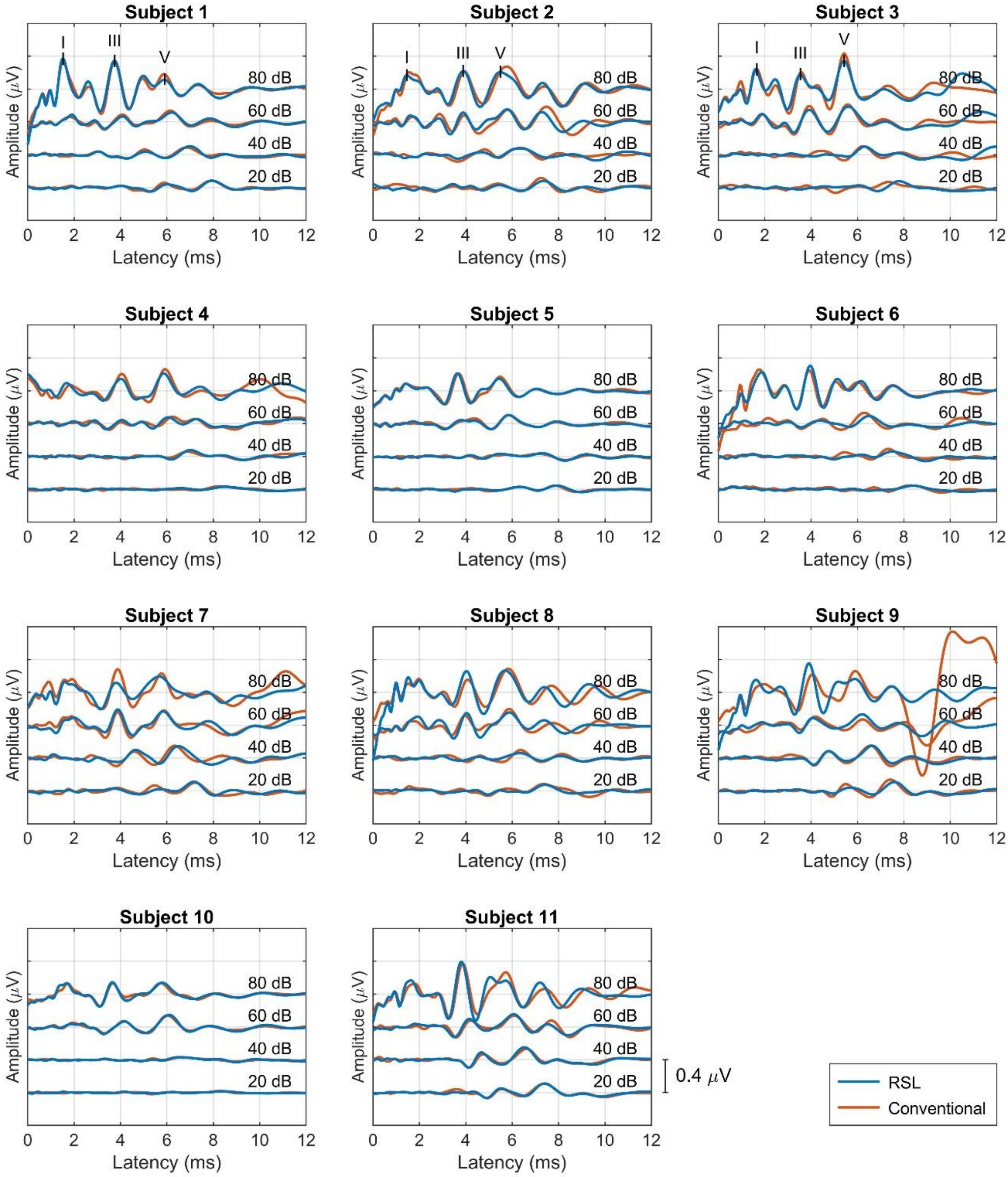
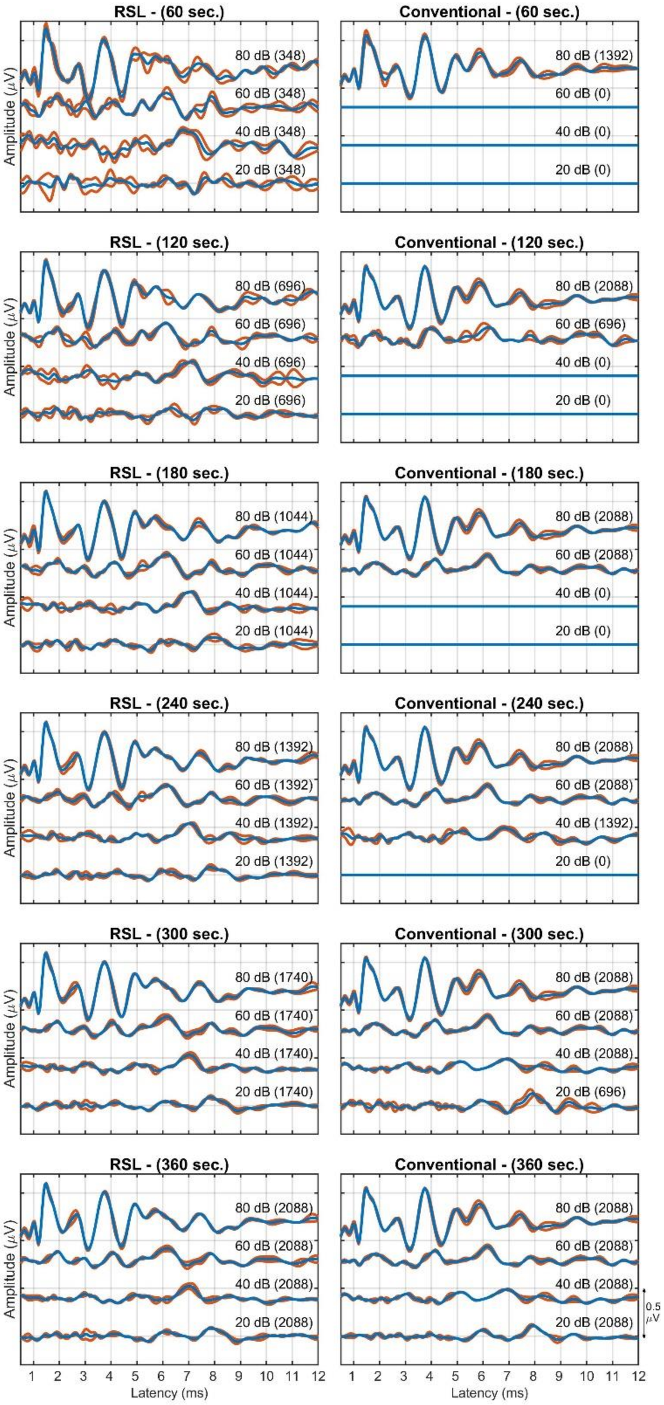
Figures

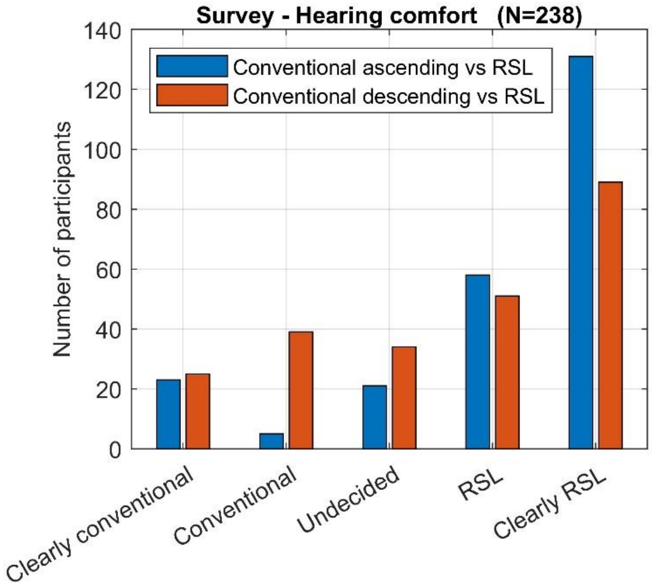
- Figure 1. Individual auditory brainstem responses obtained with the conventional and randomised stimulation level (RSL) stimulus paradigms at different hearing levels. Waves I, III and V are marked in the 80 dB nHL ABR traces obtained with RSL in the first three subjects.



- Figure 2. Video snapshots that re-create the ABR recording process for subject 1 using the RSL (left column) and the conventional (right column) techniques at different time intervals, when the conventional mode is presented in descending level. The number of averaged sweeps per ABR trace is presented in brackets. The video snapshots for the remaining subjects with the conventional technique implemented in ascending and descending levels is presented as supplementary material in Section 3 of Appendix A.



- Figure 3. Hearing comfort preference between the conventional and randomised stimulation level (RSL) paradigms reported by 238 adults, with the conventional paradigm presented in both ascending and descending level.



Tables

- Table 1. Mean (μ) and standard deviation (σ) of the latency (ms) and amplitude (μV) of waves I, III and V for the conventional and randomised stimulus level (RSL) paradigms at different levels (dB nHL).

		Latencies (ms)				Amplitudes (μV)			
		Conventional		RSL		Conventional		RSL	
		μ	σ	μ	σ	μ	σ	μ	σ
Wave I	80 dB	1.67	0.18	1.60	0.13	0.36	0.13	0.38	0.12
	60 dB	2.08	0.36	2.16	0.46	0.14	0.07	0.14	0.08
	40 dB	3.06	0.38	3.06	0.43	0.07	0.04	0.05	0.03
	20 dB	3.85	0.36	3.47	0.78	0.08	0.02	0.05	0.02
Wave III	80 dB	3.85	0.17	3.84	0.17	0.40	0.13	0.42	0.16
	60 dB	4.21	0.31	4.18	0.30	0.17	0.09	0.17	0.08
	40 dB	5.03	0.44	4.97	0.52	0.08	0.05	0.07	0.05
	20 dB	5.90	0.43	5.63	0.61	0.07	0.04	0.04	0.03
Wave V	80 dB	5.78	0.19	5.71	0.21	0.34	0.11	0.33	0.10
	60 dB	6.01	0.22	6.02	0.26	0.22	0.07	0.21	0.06
	40 dB	6.64	0.35	6.75	0.42	0.14	0.06	0.14	0.05
	20 dB	7.71	0.46	7.83	0.47	0.12	0.05	0.11	0.04

- Table 2. Waveform quality measured as signal-to-noise ratio (SNR) in the conventional and randomised stimulation level (RSL) paradigms. Rows 2 to 13 show mean SNR values averaged across levels for each participant; and rows 14 to 18 show the mean SNR values at different levels, averaged across participants. The raw data of this table can be found in the supplementary materials (Appendix A, Section 2).

	RSL	Conventional	Improvement
Subject 1	14.39 dB	16.08 dB	-1.69 dB
Subject 2	11.40 dB	9.13 dB	2.27 dB
Subject 3	5.84 dB	9.76 dB	-3.91 dB
Subject 4	7.56 dB	8.37 dB	-0.80 dB
Subject 5	14.74 dB	9.81 dB	4.94 dB
Subject 6	8.72 dB	10.02 dB	-1.30 dB
Subject 7	8.21 dB	6.12 dB	2.09 dB
Subject 8	11.99 dB	8.07 dB	3.92 dB
Subject 9	16.61 dB	9.59 dB	7.02 dB
Subject 10	15.87 dB	12.20 dB	3.67 dB
Subject 11	18.85 dB	12.67 dB	6.18 dB
Average	13.93 dB	11.03 dB	2.90 dB
80 dB nHL	17.48 dB	13.59 dB	3.90 dB
60 dB nHL	13.17 dB	10.94 dB	2.24 dB
40 dB nHL	10.98 dB	8.50 dB	2.48 dB
20 dB nHL	9.77 dB	9.22 dB	0.55 dB
Average	13.93 dB	11.03 dB	2.90 dB