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Repeatability of sound evoked triceps myogenic potentials

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Abbreviations: cervical vestibular evoked myogenic potentials (cVEMP), sound evoked myogenic potentials recorded from the triceps (tVEMP)

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Abstract

Objective: To investigate the repeatability of sound evoked vestibular evoked myogenic potentials recorded from the triceps (tVEMPs) with and without visual feedback.

Design: tVEMP responses to 95 dB nHL 500 Hz tone bursts were recorded in a longitudinal, repeated measures study where P1 and N1 latencies and amplitudes were measured on three separate occasions from the same individuals. Analysis of variance, intra-class correlations and limits of repeatability analysis were used to assess tVEMP repeatability and effects of visual feedback.

Study Sample: 15 participants (9 women) aged between 18 and 41 years took part.

Results: Response rates of 63 % and 68 % were obtained for tVEMPs with eyes open and closed, respectively. When present, tVEMP latencies and amplitudes exhibited fair to good repeatability. Repeatability of tVEMP latencies and amplitudes measured using Bland-Altman methods was poorer with eyes closed.

Conclusions: Sound evoked tVEMP response rates are too low to support their clinical utility at the moment. tVEMP response rate may be improved by refining the balance task to include a force related target. Better tVEMP repeatability with eyes open supports the hypothesis that the response is modulated by visual feedback, and is consistent with studies reporting triceps responses to galvanic stimulation.

Introduction

The measurement of Vestibular Evoked Myogenic Potentials (VEMPs) exploits the sensitivity of the vestibular system to sound stimulation. Neurophysiological studies in animals have revealed that air-conducted sound stimuli activate both the saccule and utricle of the otilith system (Murofushi et al., 1995; Curthoys et al., 2012). This activation can cause measurable changes in muscle activity, but the precise origin of the myogenic response is dependent upon the recording site. For example, VEMPs evoked by loud air-conducted acoustic click stimuli recorded from the tonically contracted sternocleidomastoid (SCM) muscle of the neck are likely to originate in the saccule, because the response recorded in that muscle is predominently determined by saccular activation, but not because the stimulus only activates saccular afferents. Similarly, ocular VEMPs (oVEMPs) recorded from extra-ocular muscles in response to air-conducted sound (Chihara et al., 2007; Iwasaki et al., 2008) are thought to originate in the utricle (Curthoys, 2010; Jacobson et al., 2011) because the muscle response is predominently determined by activation of utricular afferents, not utricle-specific activation by the stimulus.

The majority of studies investigating the clinical potential of VEMPs have focused on those recorded from the SCM muscle (Colebatch & Halmagyi, 1992; Colebatch et al., 1994; Versino et al., 2001; Chang et al., 2007), referred to as cervical VEMPs (cVEMPs). The cVEMP is attractive clinically since it has a high response rate (Wang & Young, 2006; Maes et al., 2009) and comprises an easily recordable and identifiable waveform (Debatisse et al., 2005). Data from animal models suggest that the input to the SCM is predominantly from the saccular macula with air-conducted acoustic click stimulation (Curthoys, 2010). cVEMPs therefore provide a clinical measure of an aspect of the vestibular system often neglected by

routine clinical test batteries which focus on the horizontal semi-circular canal and superior portion of the vestibular nerve, via the use of the caloric and/or rotating chair tests.

Sound evoked myogenic potentials have also recently been recorded from muscles below the neck, specifically the gastrocnemius (Rudisill & Hain, 2008) and triceps (Cherchi et al., 2009) muscles. In contrast to cVEMPs, which are primarily found ipsi-laterally to acoustic stimulation, sound evoked myogenic potentials recorded from the gastrocnemius or triceps muscles are found both ipsi- and contra-lateral to acoustic stimulation (Rudisill & Hain, 2008; Cherchi et al., 2009). These responses have significantly smaller amplitudes and longer latencies than cVEMPs and available evidence supports vestibular rather than auditory involvement; to our knowledge only Cherchi et al. (2009) and Rudisill and Hain (2008) have previously investigated sound elicited limb responses in humans. Rudisill and Hain (2008) reported that the lower limb gastrocnemius VEMP response was absent in an individual with bilateral vestibular dysfunction but normal hearing, and the response was eliminated in a sitting healthy participant. Similarly, Cherchi et al. (2009) reported that sound elicited tVEMPs were only present when the triceps was engaged in a task relevant to balance maintenance. These characteristics suggest that, unlike cVEMPs, sound evoked limb VEMPs may have a strong association with postural control. The precise origin of the response is currently unclear, but evidence indicates that air-conducted sound is likely to stimulate both saccular and utricular afferents (Curthoys, 2010; Rosengren et al., 2010) generating a signal travelling along the superior and inferior divisions of the VIII nerve to second-order vestibular nuclei, where there are projections to oculomotor and cerebellar structures and to the spinal cord via the vestibulospinal tract. Descending pathways synapse on motor neurons that innervate the muscles involved in supporting posture and balance. Other connections are involved in multisensory integration of posture and balance relevant information (Driver &

Noesselt, 2008) and may modify the otolith signal (Welgampola & Colebatch, 2001) that modulates the surface EMG to form the averaged VEMP response.

Evidence that supports postural involvement is also provided by studies that measure reflexes in response to galvanic stimulation. In contrast to sound evoked vestibular reflexes, galvanic stimuli are thought to by-pass the end organ and stimulate more central vestibular structures in comparison to air-conducted acoustic stimuli (Bacsi et al., 2003). Galvanic evoked myogenic potentials have been successfully recorded from the soleus muscle (Baldissera et al., 1990; Britton et al., 1993; Welgampola & Colebatch, 2001; Bacsi et al., 2003) and the triceps (Baldissera et al., 1990; Britton et al., 1993). Although details of the exact pathway are currently unclear, the technique has been shown to evoke vestibular dependent spinal reflexes that would compensate for postural perturbations and could be involved in the maintenance of upright stance. Like sound evoked responses, galvanic evoked myogenic potentials can be evoked only when performing a balance task. In addition they are modulated or strongly attenuated by vision or proprioceptive information, head position, the complexity of the muscle contraction task or when vestibular input is unnecessary for stability (Britton et al., 1993; Fitzpatrick et al., 1994; Watson & Colebatch, 1997).

The current study has three aims: i) to confirm the Cherchi et al. (2009) finding that sound elicited tVEMPs can be recorded from the triceps of healthy adults and ii) to extend their study by testing the repeatability of the response. Although there are currently no standardised methods for tVEMP measurement and no information regarding their repeatability, within subject comparisons and the fair to good repeatability of cVEMPs (Versino et al., 2001; Isaradisaikul et al., 2008; Maes et al., 2009) support its clinical potential. The final aim of this study was to iii) determine if the modulation due to visual

feedback seen with galvanic elicited VEMPs (e.g. Welgampola & Colebatch, 2001) is also evident with sound elicited tVEMPs. For sound elicited tVEMPs to be clinically useful, it is important to know the nature of any sensory modulation. If changes in vestibular function due to pathology are of interest then it would be beneficial to first ensure that the response is recorded under optimal conditions. Additionally, evidence that sound-evoked triceps responses can be modulated by sensory input will provide support for the involvement of the end organ in this reflex arc and for its role in the integration of vestibular and other sensory information in the brain. If the responses can be shown to have a defined vestibular origin then there are several potential clinical applications for tVEMPs; these responses may provide an additional useful measure of vestibular function, for example, evaluation of vestibulospinal pathways and vestibular disorders associated with cervical spinal cord lesions (Cherchi et al., 2009); or in developing a better understanding of the definitions and underpinning mechanisms of suspected cervical vertigo (Brandt & Bronstein, 2001).

Materials and Methods

Participants

Fifteen healthy adult volunteers aged between 18 and 41 years (mean = 23.6; 9 female) with no history of hearing or vestibular problems, were recruited to this study. All participants underwent pure tone audiometry and tympanometry and had air conducted hearing thresholds better than 20 dB HL at octave frequencies between 0.5 and 6 kHz and normal middle ear function in both ears. Ethical approval for this study was granted by the School of Healthcare Research Ethics Committee at the University of Leeds.

Sound evoked myogenic potential recording

All responses were recorded using a Bio-Logic Navigator-Pro system (Bio-Logic Systems Corp, Mundelein, USA) and associated auditory evoked potential software (version 5.1.0). Electro-myogenic signals were recorded using disposable silver-silver chloride electrodes positioned on the belly of the triceps or SCM muscle and the reference electrodes were positioned on the sternum (Rudisill & Hain, 2008; Cherchi et al., 2009). All electrode impedances were less than 5 kOhms. Air-conducted 500 Hz tone-bursts (rise/fall time = 1 ms; plateau time = 2 ms) were delivered monaurally at 95 dB nHL to the test ear via Telephonics TDH-39P headphones at a repetition rate of 5 Hz. 200 sweeps of the un-rectified EMG were averaged for each recording method, using an epoch of 106.6 ms and gain set at x5000. All responses were band-pass filtered (12 dB/octave) between 10-1500 Hz.

cVEMPs were recorded ipsi-laterally to monaural stimulation using the head rotation method of muscle contraction which has been shown to be a reliable method for recording this reflex (Vanspauwen et al., 2006). Participants were seated in a comfortable chair and asked to rotate their head away from the test ear, toward the contralateral shoulder, and push their cheek against a blood pressure manometer to maintain a pre-specified level of 40 mm Hg. This enabled the testers and participants to monitor and maintain a consistent level of SCM contraction (Vanspauwen et al., 2006).

tVEMPs were recorded contralateral to monaural stimulation with eyes open and closed. Participants were asked to look straight ahead, to stand at an arm's length away from the wall of the test room with their legs together and to lean against the wall using the arm contralateral to the acoustic stimulus, bent at the elbow at an angle of approximately 160^{o}

(see Figure 1). Participants were asked to keep their head straight during recordings. Participant position, arm angle and on-going un-rectified EMG were monitored throughout the recording to ensure the triceps were activated consistently.

Procedure

Informed consent was obtained and audiological screening carried out prior to the myogenic potential tests. Participants underwent cVEMP and tVEMP testing at each of the three recording sessions (T1-T3) at weekly intervals. cVEMPs were recorded first, followed by tVEMPs recorded with eyes open and closed, in random order. The first test ear for each recording block was chosen randomly. For each recording technique, measurements were made at least twice in each session and for each condition to ensure waveforms were repeatable. A rest period of at least 5 minutes was provided between each recording to prevent muscle fatigue.

Results

Figure 2 shows examples of tVEMP and cVEMP waveforms from two representative participants. Clear cVEMPs were recorded at T1 from 28 of 30 ears (a response rate of 93.3 %) since neither a repeatable cVEMP nor a repeatable tVEMP waveform could be recorded from the left ears of two participants at T1-T3. A further participant showed no repeatable tVEMP or cVEMP in their left ear at T2. Thus, cVEMP recordings from all three sessions were obtained from 27 ears and were included in the repeatability analysis. The picture is somewhat different for tVEMPs. In addition to the tVEMP absences noted above, the following pattern was observed in the 27 ears that exhibited cVEMPs and were included in

the study; two participants had no repeatable tVEMPs in either ear and a further three participants had unilaterally absent tVEMPs at T1-T3 (two in the left ear and one in the right ear) although right sided responses were present in one case at T1 with eyes closed. These cases were excluded from the reliability analysis. Overall, tVEMPs were recorded from 20 of the 27 cVEMP ears with the same response profile (i.e. same side and both with eyes open and closed) at T1-T3; a response rate of 74.3 %. The tVEMP response rate irrespective of cVEMP presence was 66.7 % with eyes open and with eyes closed.

Mean latencies of N1 and P1 and amplitudes for cVEMP measurements at each time interval are given in Table 1. The mean values and standard deviations for individual measurements are broadly similar for each replication. To further investigate potential differences in the variation across the recording sessions, a repeated measures ANOVA with replication (three replications in all) as a factor was applied separately to the three measures of N1, P1 and amplitude. No significant main effect of replication was seen for cVEMP amplitudes ($F_{2,25}$ = 1.58, p=0.22) or N1 latency ($F_{2,25}$=0.34, p=0.71). However there was a just significant effect of replication for P1 latency ($F_{2,25}$=4.95, p<0.05). Closer inspection of the estimated marginal means indicated significant mean differences between P1 latencies at T1 and T2 (mean difference = 0.70 ms, p<0.05), but not between T2 and T3 (mean difference = 0.11, p=0.77).

Mean tVEMP N1 and P1 latencies and response amplitudes for eyes open and closed conditions are given in Table 1. On inspection there appears to be little difference in mean values with eyes open or closed. To statistically test this observation and to test for average differences in latencies and amplitude across the three replications, a second repeated measures ANOVA with replication (T1-T3) and visual feedback (eyes open or closed) as factors was used to analyse the N1, P1 and amplitude data separately. There were no

significant main effects of visual feedback on P1 latency ($F_{1,19}$=1.23. P=0.28), N1 latency ($F_{1,19}$=0.07, p=0.79), or response amplitude ($F_{1,19}$=0.38, p=0.54). Additionally, there were no main effects of replication on P1 latency ($F_{2,18}$=0.25. p=0.79), N1 latency ($F_{2,18}$=1.60, p=0.80) or response amplitude ($F_{2,18}$= 1.85, p=0.19).

Repeated measures ANOVAs are useful in this context since they indicate differences in the variation within the sample around mean values of the data collected on each occasion. However, they provide little information regarding the reliability of measuring response data on different occasions from the same individuals. We therefore calculated intra-class correlation coefficients (ICC) for each tVEMP and cVEMP response parameter. ICCs were determined for each method using a two-way random effects, average measures model (absolute agreement). ICC values of more than 0.75 are considered to reflect excellent reliability, between 0.4 and 0.75 fair to good reliability and less than 0.4 poor reliability (Versino et al., 2001; Tabachnick & Fidell, 2006; Isaradisaikul et al., 2008; Maes et al., 2009). The values shown in Figure 3 indicate at least fair to good reliability for cVEMPs and excellent reliability for tVEMPs with eyes open and eyes closed. The ICC is the average pair wise correlation across all of the replications. It does not necessarily reflect agreement across the data recorded at each session. A low ICC can arise from low between-subject variability rather than a lack of agreement. The ICC is also dependent on the range of measurements and is not related to the actual scale of measurement or the size of error that might be clinically acceptable. Bland-Altman's 'limits of agreement' analysis (Bland & Altman, 1986; 1999; 2007) avoids some of these problems (Bland & Altman, 1986) and was used to calculate and compare limits of agreement across replicates for N1 and P1 latencies and response amplitudes for cVEMP and tVEMP methods. Within-subject standard deviations for all cVEMP and tVEMP measures were estimated from separate one-way ANOVAs with

participants as a factor. Comparison of the within-subject standard deviations indicated that the repeatability (agreement across replicates) of N1 and P1 latencies for cVEMP and tVEMP with eyes open was similar. However, cVEMP response amplitudes were 40 % more repeatable than tVEMP response amplitudes with eyes open, tVEMP P1 and N1 latencies with eyes open were both approximately 40% more repeatable than tVEMP latencies with eyes closed and tVEMP response amplitudes with eyes open were almost 70 % more repeatable than tVEMP response amplitudes with eyes closed.

Since the mean difference between replications did not differ systematically (see Table 1), we used each standard deviation to calculate the repeatability coefficient using the technique of Bland and Altman (Bland & Altman, 1999; 2007). Repeatability coefficients indicate the range within which two measurements made by the same method will be expected to lie for 95 % of people taken from a similar sample. They are commonly used in electrophysiological measurements in the field of audiology (Naves et al., 2012). The repeatability coefficients for cVEMP N1 and P1 latencies and response amplitude were 3.37 ms, 3.71 ms and 171.91 µV, respectively. For tVEMP N1 and P1 latencies and response amplitude with eyes open, repeatability coefficients were 4.37 ms, 4.57 ms and 423.79 µV, respectively. For tVEMP N1 and P1 latencies and response amplitude with eyes closed, repeatability coefficients were 11.66 ms, 11.94 ms and 615.02 µV, respectively.

Discussion

Variation in response rates and test-retest reliability of cVEMPs has been reported previously (Wang & Young, 2006; Isaradisaikul et al., 2008; Maes et al., 2009; Isaradisaikul et al., 2012) and our response rates (93 %) are broadly comparable. The reason for the just

significant mean latency difference between T1 and T2 (but not T3) for the averaged cVEMP P1 response component, remains unclear. The procedure was unchanged at each epoch and a similar finding was not seen in the N1 component. The explanation may simply be related to insensitivity of the ANOVA to detect reliability as noted in the results section. Our tVEMP data confirm the Cherchi et al. (2009) finding that sound evoked VEMPs can be recorded from the triceps when activated in a balance related task. However, to be considered a viable clinical test of vestibulospinal pathways, it must be demonstrated that tVEMP response rates are clinically relevant and at least equivalent to those achievable with other VEMP responses, such as cVEMPs. Our data indicate that tVEMPs obtained using the current method of triceps activation and surface EMG monitoring are not sufficiently reliable for clinical use. Nevertheless, when present, tVEMP and cVEMP repeatability was broadly similar, although cVEMP amplitudes were considerably more repeatable than tVEMP responses with eyes open. This observation and the finding that sound evoked tVEMP amplitudes and latencies appear to be significantly more repeatable with eyes closed than with eyes open is of interest and is consistent with the observation that vestibulospinal, but not vestibulocollic, reflexes are modulated by sensory (including visual) input under galvanic stimulation (Welgampola & Colebatch, 2001).

tVEMP Response Rates

That we found different response rates for tVEMPs and cVEMPs is not surprising since the former derives from the vestibulospinal reflex and the latter the vestibulocollic reflex and these reflexes have different anatomical pathways, physiological purpose and inputs (Uchino & Kushiro, 2011). Empirical evidence for differing tVEMP response rates is scarce. The only other published study of acoustically evoked tVEMPs (Cherchi et al., 2009) reported

tVEMP response rates of 100 % in adult participants with normal cVEMPs, although it is not explicitly stated whether the exclusion criteria included absent tVEMPs. Nevertheless, this value is substantially higher than our response rate for both eyes open (63 %) and eyes closed (68 %).

Our procedure was similar to that used by Cherchi et al. (2009) except that, where we relied upon observation of on-going EMG to check muscle activation, they adjusted participants' stance to achieve a target force measured with a pressure sensor. Force is not directly related to triceps muscle activation, since individuals with larger muscles might use less muscle activation to deliver the same force compared to a person with smaller muscles. Nevertheless, since VEMP amplitude increases with increasing force (Lim et al., 1995; Akin et al., 2004; Rosengren et al., 2010) using force as a measure at least ensures that the triceps has a substantial activation leading to a measurable tVEMP. The surface EMG, which we used to check muscle activation, is present whether the triceps is slightly activated or fully activated. Therefore, the closer control on muscle activation reported in Cherchi's study, may be the reason why tVEMP's were obtained in all of their participants, and explain the absence of tVEMPs in some of our participants. The implication is that direct observation of on-going EMG alone may not be a reliable marker of sufficient triceps contraction to record inhibition in the EMG. Comparison of tVEMP amplitudes obtained in the current study with the inter-peak amplitudes reported by Cherchi et al. (2009) suggest that in many cases our method was sufficient to ensure adequate muscle activation. Interestingly, similar levels of on-going EMG activity were observed in participants for whom no averaged tVEMP could be recorded compared to those with a clearly recorded tVEMP. Thus, it may be concluded that both checking the EMG and ensuring that a criterion force was exerted would be a better method than monitoring force or EMG levels alone.

The absence of an averaged tVEMP response suggests that either the support task did not sufficiently engage the triceps in balance for these participants or that multiple sensory inputs were sufficient to reduce the vestibular input to a level below the noise floor. One resolution may be to adopt a different balance related task for these measurements, such as that used by Britton et al. (1993) whereby the triceps were actively used to maintain balance on an unstable support surface. If the force used to maintain balance under these circumstances is set as a criterion and EMG is checked then the likelihood of a response and response rates may increase. The cause of the difference in tVEMP response rates reported here and by (Cherchi et al., 2009) remains unclear, due to procedural differences for quantifying triceps activity, but indicates a need for studies to further refine and monitor the balance task to ensure the triceps is activated using force feedback.

tVEMP variability between participants.

The mean tVEMP parameter values and their SDs shown in Table 1 indicate that there is a high level of variability in the between-subject amplitude data for tVEMPs with eyes open and closed and for cVEMPs as reported previously (Isaradisaikul et al., 2008; Bush et al., 2010). This variability can be explained by the uncertainty that exists regarding the relationship between muscle contraction level and VEMP amplitude. Whilst methods have been proposed to reduce this variability by using pre-stimulus EMG to normalize the VEMP (Colebatch et al., 1994; Lee et al., 2008), recent evidence (Bogle et al., 2013) suggests that because surface EMG is not proportional to VEMP amplitude, dividing the response amplitude by surface EMG is not "normalization", as this presupposes a proportional relationship. This leaves us with an inherently variable absolute measure of VEMP

amplitude which is probably exacerbated by averaging techniques commonly used that (incorrectly) assume independence between background EMG and the response (Bogle et al., 2013). This adds a further layer of uncertainty to the relationship between muscle contraction level and VEMP amplitude. The same level of variability is not evident in VEMP latencies irrespective of stimulus, recording site or technique (Britton et al., 1993; Bacsi et al., 2003; Welgampola et al., 2003; Cherchi et al., 2009).

tVEMP Repeatability

When tVEMP responses were consistently present across the three sessions, each parameter was reliable. Analysis of variance indicated that mean latency and amplitude values were relatively stable across replications and the ICCs obtained suggested good repeatability for all tVEMP response parameters. The clinical relevance of the repeatability data however, is more obvious when Bland–Altman repeatability coefficients are analysed. These coefficients indicate the limits within which we would expect the difference between two further measurements to lie using the same method in 95 % of observations made from the same population. For example, if the mean N1 and P1 tVEMP eyes open latencies in week 1 are considered, it would be expected that subsequent measurements from the same participant would fall within 5 ms of these values. This does not seem unreasonable, although in the absence of published large scale normative data or data from populations with known pathologies, the clinical significance of any variation in values is yet to be established. The limits of repeatability increase to almost 12 ms when we consider tVEMPs with eyes closed. Similarly, there is an increase in the limits of repeatability associated with amplitude with eyes closed. From these data, we would expect subsequent within-subject amplitude responses to fall within approximately 400 µV and 600 µV for tVEMP with eyes open and

eyes closed, respectively. Given that these amplitude limits of repeatability are of a similar order of magnitude to the absolute mean amplitudes (Table 1), the clinical utility of this parameter measured in this study remains questionable for the moment. This argument is less critical when we compare the latency limits of repeatability with their mean values. The more stable latency values, within each condition, may prove to be more clinically useful. The finding that Bland-Altman repeatability coefficients for both tVEMP latencies were more than doubled and increased by a factor of 1.5 for response amplitudes when recordings were made with eyes closed is of interest, particularly when we consider the evidence for sensory modulation of vestibulospinal reflexes from galvanic stimulation studies (Baldissera et al., 1990; Britton et al., 1993; Welgampola & Colebatch, 2001; Bacsi et al., 2003).

No other study has investigated the influence of visual feedback in sound evoked tVEMPs, but our finding is consistent with other research that indicates a role for sensory modulation of galvanic evoked EMG recorded in posturally relevant lower limb and triceps muscles. Since galvanic stimulation probably by-passes the end-organ (Bacsi et al., 2003; Day et al., 2011) we would expect these effects to also be present with acoustic stimulation of the vestibulospinal reflex pathway. The results of this study provide early evidence in support of this. The importance of considering both modes of stimulation is that, used together, the techniques could potentially provide a useful differential diagnosis of vestibular function. In this study we confirmed and extended the research carried out by Cherchi et al. (2009). We demonstrated that tVEMP latencies, at least, are as repeatable as those recorded from the SCM and that the variability in response amplitudes probably limits their clinical utility at this time. Further investigation of the sound evoked tVEMP will help determine optimum recording techniques that maximize response rates and will explore the influence of visual and somatosensory inputs that will characterize the response further.

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Table 1 - Mean (SD) N1 and P1 latencies (ms) and amplitudes (µV) measured at three one week intervals

Procedure	Measure	Week 1	Week 2	Week 3
cVEMP N=27 ears	N1	24.98 (2.35)	25.20 (2.64)	25.30 (2.50)
	P1	15.57 (1.50)	16.26 (1.83)	16.37 (1.86)
	Amplitude	86.32 (78.29)	65.52 (83.25)	61.46 (49.42)
tVEMP (eyes open) N=19 ears	N1	45.19 (5.03)	45.44 (4.74)	45.45 (4.19)
	P1	39.17 (4.54)	39.33 (4.59)	39.28 (4.28)
	Amplitude	228.53 (171.85)	275.80 (225.31)	334.66 (241.13)
tVEMP (eyes closed) N=20 ears	N1	44.83 (4.57)	45.67 (4.60)	45.10 (4.62)
	P1	38.60 (4.57)	39.08 (4.46)	38.80 (4.43)
	Amplitude	281.26 (153.44)	249.48 (206.10)	332.16 (256.72)

Figure 1 – Participant position adopted for tVEMP testing

For tVEMPs, participants were asked to stand just under an arm's length away from the wall of the test booth with their legs together, feet flat on the ground and to lean against the wall using the arm contralateral to the acoustic stimulus, bent at the elbow at an angle of roughly 160º.

Figure 2 – Example cVEMP and tVEMP response waveforms

cVEMP (left) and tVEMP (eyes open, right) waveforms obtained from two participants (A, top) and (B, bottom) during a single recording session. Each response was evoked by presenting a 500 Hz 95 dB nHL tone-burst to the left ear.

Figure 3 – Intra-class correlation coefficients (ICC) for tVEMP (eyes open and closed) and cVEMP

cVEMP response parameters exhibited at least fair-good repeatability and tVEMP responses exhibited excellent repeatability. < 0.4 represents poor repeatability, 0.4 and 0.75 represents fair-good repeatability and > 0.75 represents excellent repeatability. Bars indicate 95% confidence intervals for upper and lower ICC bounds.