Hearing Research 345 (2017) 88–95

Contents lists available at ScienceDirect

Hearing Research

journal homepage: www.elsevier.com/locate/heares

Research Paper

Using acoustic reflex threshold, auditory brainstem response and loudness judgments to investigate changes in neural gain following acute unilateral deprivation in normal hearing adults

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ARTICLE INFO

Article history:
Received 15 September 2016
Received in revised form
10 January 2017
Accepted 11 January 2017
Available online 16 January 2017

Keywords:
Unilateral deprivation
Neural gain
Subcortical plasticity

ABSTRACT

Unilateral auditory deprivation induces a reduction in the acoustic reflex threshold (ART) and an increase in loudness. These findings have been interpreted as a compensatory change in neural gain, governed by changes in excitatory and inhibitory neural inputs. There is also evidence to suggest that changes in neural gain can be measured using the auditory brainstem response (ABR). The present study extended Munro et al. (2014) [J. Acoust. Soc. Am. **135**, 315–322] by investigating changes after 4 days of unilateral earplug use to: (i) ART, (ii) ABR and (iii) loudness. Because changes may occur during the post-deprivation test session (day 4), ART measurements were taken 1 h and 2 h post-earplug removal. There was a significant reduction in ART in the treatment ear immediately after the removal of the earplug, which is consistent with a compensatory increase in neural gain. A novel finding was the significant return of ARTs to baseline within 2 h of earplug removal. A second novel finding was a significant decrease in the mean amplitude of ABR wave V in the treatment ear, but a significant increase in the control ear, both after 4 days of deprivation. These changes in the ABR are in the opposite direction to those predicted. We were unable to replicate the change in loudness reported in previous deprivation studies; however, the short period of earplug use may have contributed to this null finding.

1. Introduction

Changes in the acoustic environment or hearing loss (real or simulated) can trigger a variety of adaptive mechanisms in the auditory brain. For example, a long-term reduction in auditory input can result in an increase in neural activity in response to a subsequent stimulus. This is achieved by scaling the strength of excitatory responses up and inhibitory responses down (Turrigiano, 1999). These changes have been investigated in humans using perceptual measurements such as loudness, and physiological measurements such as the acoustic reflex threshold (ART: the sound level required to elicit a contraction of the stapedius muscle in the middle ear) and the auditory brainstem response (ABR: an objective measure of neural activity in ascending auditory brainstem structures).

A change in loudness has been reported after using bilateral earplugs and noise generators (Formby et al., 2003, 2007). The change was observed in both ears and of a similar magnitude at 0.5 and 2 kHz, despite a difference in earplug attenuation at these frequencies. A similar pattern of change between the ears has also been reported after unilateral earplug use (Munro et al., 2014) and unilateral acoustic stimulation (Munro and Merrett, 2013). For example, using the categorical loudness test (Cox et al., 1997),

Abbreviations: ABR, auditory brainstem response; AN, auditory nerve; ART, acoustic reflex threshold; BBN, broadband noise; CN, cochlear nucleus; DCN, dorsal cochlear nucleus; ECV, ear canal volume; IC, inferior colliculus; IHC, inner hair cells; LL, lateral lemniscus; NIHL, noise induced hearing loss; SOC, superior olivary complex; VCN, ventral cochlear nucleus

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http://dx.doi.org/10.1016/j.heares.2017.01.009
0378-5955/

Munro et al. (2014) reported a 5 dB decrease in sound level required to match pre-treatment loudness, at 0.5 and 2 kHz in both ears of normal hearing listeners after 7 days of unilateral earplug use. These changes in loudness can be interpreted as a frequency-independent change in neural gain that occurs in both ears.

All studies that have investigated the ART after short-term unilateral deprivation have reported a different pattern of change in each ear. For example, Munro et al. (2014) reported a reduction in ART in the treatment ear after 7 days of unilateral earplug use in normal hearing listeners. In contrast, an increase in ART occurred in the control ear. This change was greatest at the high frequencies where the earplug provided greatest attenuation. A similar change was reported after increased unilateral acoustic stimulation (Munro and Merrett, 2013). The change in ART has been interpreted in terms of a compensatory change in neural gain operating at the lower level of the brainstem (Munro et al., 2014), which may attempt to counterbalance/reduce the asymmetry between the ears. ART measurements have not been made after bilateral changes in auditory input. Munro et al. (2014) also reported that most of the asymmetry between the two ears had disappeared within 24 h of earplug removal.

The exact location of the physiological changes in the lower auditory brainstem remains unknown. Decker and Howe (1981) were unable to demonstrate a significant change in the amplitude of the ABR following 10–30 h of unilateral earplug use. However, as the deprivation period was relatively short, the ABR measurement may not have been sensitive enough to detect small changes in central neural gain. The authors did report a significant reduction in wave I latency. This is consistent with a decrease in neural conduction time at the level of the auditory nerve, which could be due to a change in the synchronous activity of neuronal populations (Skoe and Kraus, 2010), and is therefore not consistent with an increase in neural gain.

The present study extended that of Munro et al. (2014) by investigating ART, ABR and loudness after short-term unilateral deprivation. It was hypothesized that unilateral earplug use would induce a reduction in ART in the treatment ear and an increase in ART in the control ear. It was also hypothesized that there would be an increase in the amplitude of wave III and V of the ABR in the treatment ear and a decrease in the control ear. This would be consistent with a neural gain mechanism that operates at the level of the cochlear nucleus (CN), the main generator of wave III (Kaltenbach et al., 2000; Mulders and Robertson, 2009). The present study also measured loudness in order to investigate if changes could be observed over a shorter period of deprivation than that used in previous studies. It was hypothesized that loudness to a given test stimulus would increase after 4 days of unilateral earplug use, based on evidence of a change in loudness after 3 and 5 days by Munro and Merrett (2013). Finally, the ART was measured approximately 1 and 2 h after earplug removal in order to characterise changes in neural gain within the post-deprivation test session.

2. Methods

2.1. Participants

We calculated the sample size based on preliminary data from our laboratory. For the ART measurements, a power analysis revealed that 13 participants were required for a power of 80%, assuming a within-subject difference of 4 dB (s.d. ± 6) on a two-tailed paired samples *t*-test at 5% significance level. For the ABR, we did not have a good estimate of effect size. Therefore, we based the sample size on previous ABR research by Schaette and McAlpine (2011) and Gu et al. (2012), which had sample sizes ranging from 15 to 21. For the categorical loudness judgments, the analysis revealed that 28 participants were required for a power of 80%, assuming a within-subject difference of 5 dB (s.d. ± 9) on a two-tailed paired samples *t*-test at 5% significance level. Thirty-two participants initially took part in the study, which received ethics approval from The University of Manchester (ref: ethics/14261). However, four participants could not complete the study due to time constraints. As a result, 28 consenting volunteers (22 females and six males; median age, 22.5 years; range 19–50 years) participated in the study. Of those completing the study, 15 participants completed the ABR recording first and 13 completed loudness tests first. All participants were screened for normal hearing sensitivity [<20 dB hearing level (HL) from 0.25 to 8 kHz and no asymmetry >10 dB at any frequency] and normal middle-ear function on tympanometry (middle ear pressure +50 to −50 daPa, middle ear compliance 0.3–1.5 cm^3).

2.2. Noise-attenuating earplugs

The participants were fitted monaurally (14 left ear, 14 right ear) with a reusable Mack's silicone putty ear plug (McKeon Products, United States) and instructed to wear it continuously for 4 days, except for daily ablutions. The length of deprivation is based on the findings of Brotherton et al. (2016) where the change in ART in the treatment ear reached maximum 4 and 6 days after unilateral earplug use.

Sound attenuation of the earplug (i.e., the difference in ear-canal sound level with and without the earplug *in situ*) was measured using a clinical probe-tube microphone system. A calibrated probe tube microphone was inserted into the ear canal and the response to a 65 dB sound pressure level (SPL) pink noise signal was measured before and after inserting the earplug. The measures were made three times on each listener after the participant removed and refitted the earplug into each ear. The mean attenuation levels across the different fittings and the average attenuation level is shown in Fig. 1. The mean attenuation levels were 13–20 dB at 0.5–1 kHz and 30 dB at 2–4 kHz. The attenuation values were similar to the levels reported by Munro et al. (2014). The mean difference between the attenuation values between each frequency were analyzed using paired *t*-tests. There were significant differences between 0.5 and 1 kHz, 0.5 and 2 kHz and 0.5 and 4 kHz ($t(27.0) = -6.69$, $p < 0.001$; $t(27) = -18.02$, $p < 0.001$; $t(27) = -8.30$, $p < 0.001$, respectively), and between 1 and 2 kHz, and 1 and 4 kHz ($t(27.0) = -22.83$, $p < 0.001$; $t(27.0) = -6.24$, $p < 0.001$), which survived after Bonferroni correction (0.05/8) for

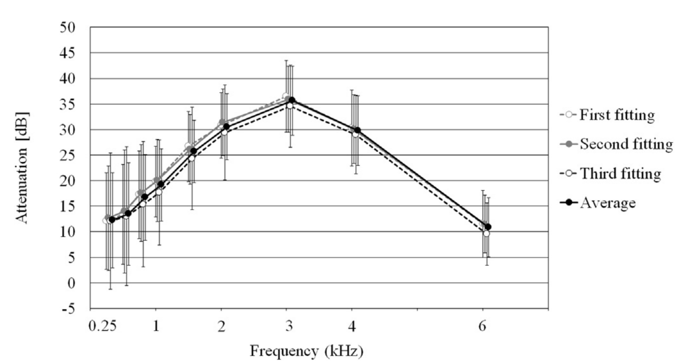

Fig. 1. Mean attenuation values taken on day 0 of earplug use for the first fitting (grey open circle with dotted line), second fitting (grey closed circle with solid line), third fitting (black open circle with dotted line) and the average attenuation values averaged across the three fittings (black closed circle with solid line). Errors bars show ± 1 standard deviation ($n = 28$).