Experience-related changes in the adult auditory system

KEVIN J. MUNRO[1,2,*], PIERS DAWES[1], AND MICHAEL MASLIN[1]

[1] *School of Psychological Sciences, University of Manchester, Manchester M13 9PL, UK*

[2] *Central Manchester University Hospitals NHS Foundation Trust Academic Health Science Centre, Manchester M13 9WL, UK*

Changes in the auditory environment, as a result of deprivation or stimulation, modify our sensory experience and may result in experience-related or learning-induced reorganisation within the central nervous system. Electrophysiological and imaging techniques have revealed reorganisation of the adult human auditory map, for example, after sudden unilateral hearing loss. In parallel to these studies, there is behavioural evidence that auditory function can be modified by changing the acoustic environment; for example, experience with amplification may have consequences for long-term performance. Future studies could usefully unite these behavioural and advanced objective techniques in order to provide a direct link between changes in perception and reorganisation of the auditory system. In this paper, we summarise our work investigating changes in perceptual and physiological measures, in adult humans, after the sensory environment has been modified by: (i) amplification, (ii) short-term sound treatment, and (iii) unilateral deafness. The findings are consistent with the growing body of literature that shows that the mature central auditory system is malleable and is modified by experience.

INTRODUCTION

Changes in the sensory environment, as a result of deprivation or stimulation, modify our sensory experience and may result in experience-related or learning-induced reorganisation within the central nervous system. Probably the most spectacular (and most commonly cited) example of injury-induced reorganisation is 'phantom limbs', a term coined by Silas Weir Mitchell to describe the sensation that an amputated limb is still attached to the body and moving appropriately. In 1871, Weir Mitchell described an amputee with a phantom limb as follows: *"A person in this condition is haunted… by a phantom of himself… an unseen ghost of the lost part."* Ramachandran *et al.* (1992) suggested that phantom limb sensations could be due to reorganization in the somatosensory cortex. Yang *et al.* (1994) were the first to demonstrate direct evidence of cortical reorganisation and its perceptual correlate: stimulation of the face and hand resulted in cortical activity in the area vacated by the amputated hand and this was perceived by the amputee as stimulation of the phantom limb.

*Corresponding author: kevin.munro@manchester.ac.uk

Proceedings of ISAAR 2013: Auditory Plasticity – Listening with the Brain. 4th symposium on Auditory and Audiological Research. August 2013, Nyborg, Denmark. Edited by T. Dau, S. Santurette, J. C. Dalsgaard, L. Tranebjærg, T. Andersen, and T. Poulsen. ISBN: 978-87-990013-4-7. The Danavox Jubilee Foundation, 2014.

Electrophysiological and imaging techniques have also revealed plasticity in sensory systems including the adult human auditory system. In parallel to these studies, there is behavioural evidence that auditory function can be modified by changing the acoustic environment; for example, experience with amplification may have consequences for long-term performance. In this paper, we summarise our work investigating changes in perceptual and physiological measures, in adult humans, after the sensory environment has been modified by: (i) experience with amplification, (ii) short-term use of sound treatments (earplug or hearing aid), and (iii) sudden and severe unilateral deafness. The findings are consistent with the growing body of literature showing that the mature central auditory system is malleable and is modified by experience. An understanding of the underlying mechanisms associated with experience-related changes in the normal and impaired auditory system is a pre-requisite to the development of more effective treatments for hearing and hearing-related disorders.

CHANGES INDUCED BY AMPLIFICATION

Deprivation and acclimatization refer to the concept that the ability to use auditory information may be affected by listening experience: Deprivation implies that the absence of experience leads to a decline in ability whereas acclimatization implies that auditory experience leads to an improvement in auditory ability (Arlinger *et al.,* 1996). Hearing aids change the sensory environment by stimulating a deprived auditory system, and therefore may induce changes within the auditory system. The earliest studies that investigated improvements in performance following hearing-aid use were motivated by the clinical need to know when best to measure hearing-aid benefit (i.e., at the time of fitting or after a period of hearing-aid use). More recent studies have been motivated by a desire to understand the dynamic nature of the mature auditory system.

Most acclimatization research has focused on loudness perception and speech recognition in noise (see reviews by Munro, 2008; Palmer *et al.,* 1998; Turner *et al.,* 1996). Gatehouse (1989) reported that speech recognition in the fitted ear of unilateral hearing-aid users was better than in the non-fitted ear for high presentation levels, while recognition was worse in the fitted ear than the non-fitted ear for low presentation levels. Gatehouse concluded that acclimatization involved adjustment to a dynamic range consistent with the gain provided by hearing aids.

Gatehouse (1992) then tested speech recognition in four new hearing-aid users over the first few months of hearing-aid use. Various listening conditions were simulated over headphones. Gatehouse reported improvements in speech recognition in listening conditions that matched the pattern of amplification provided by the hearing aid, but not in conditions with an unfamiliar pattern of amplification or in unaided listening conditions.

Munro and Lutman (2003) also tested speech recognition in the first months following hearing-aid fitting. They reported greater improvements in aided speech recognition for higher intensity speech stimuli over lower ones. In line with

Gatehouse's (1989) suggestion that changes relate to particular listening conditions, Munro and Lutman (2003) concluded that acclimatization effects occur specifically for those aspects of the stimulus that have been altered by the hearing aid and which have not been usually experienced in daily life prior to amplification. In parallel with behavioural studies, other studies have shown evidence of asymmetric ABR and cortical ERPs in experienced unilateral hearing-aid users (Gatehouse and Robinson, 1996; Munro *et al.*, 2007; Bertoli *et al*., 2011).

Evidence for acclimatization to hearing aids is inconsistent, however. One review concluded that acclimatization effects – if they do exist – were likely to be insignificantly small and not of clinical relevance (Turner and Bentler, 1998), while others contend that acclimatization effects do have clinical relevance (Palmer *et al.*, 1998). Various aspects of experimental design may explain the inconsistency in research findings, such as inclusion of participants with previous hearing-aid experience (e.g., Bentler *et al*., 1993) or participants with a heterogeneous mix of signal processing or fitting schemes (e.g., Saunders and Ceinkowski, 1997) or relatively mild levels of hearing loss (Palmer *et al.*, 1998), use of a control condition rather than a separate control group (e.g., Gatehouse, 1992; Munro and Lutman, 2003) or lack of control group (e.g., Reber and Kompis, 2005), and delays in the initial testing following fitting (e.g., Taylor, 1993).

We recently completed a longitudinal study of new hearing-aid users followed over the first months of hearing-aid use. New hearing-aid users had hearing loss of at least 1-year duration and symmetrical losses of at least 40 dB HL at 2 kHz and above and no previous experience with hearing-aid use. All new users were fitted with hearing aids with identical signal processing and fit to the same fitting formula. Accuracy and stability of fit over the study period was confirmed with real ear measures of gain. Initial testing occurred within 7 days of first fitting with retesting after 12 weeks hearing-aid use. A control group of experienced hearing-aid users was tested over the same timescale as new hearing-aid users. Tests included speech recognition in noise, spatial release from masking, auditory brainstem response (ABR), cortical auditory evoked potential (CAEP), and questionnaire measures of real life benefit. On average, new hearing-aid users showed no statistically significant changes in aided speech recognition (Dawes *et al.*, in press) or spatial release from masking (Dawes *et al.*, 2013a) over the first 12 weeks of hearing-aid use (compared to the control group). There were also no changes in ABR (Dawes *et al.*, 2013b) or cortical responses (Dawes *et al.*, submitted). New hearing-aid users did however report significant improvements in aided listening on a questionnaire measure, while no such improvements were reported by the control group (Fig. 1). This may relate to an aspect of adjustment to hearing aids not measured in this study, such as greater confidence or familiarity with hearing aids.

One possible explanation for the lack of effects in our recent acclimatization studies compared to earlier ones such as Gatehouse's is that earlier studies utilized linear-gain hearing aids while our recent studies used non-linear amplification. Non-linear hearing aids provide less amplification for higher intensity inputs than linear hearing aids. Acclimatization effects may be less robust for non-linear amplification. Our

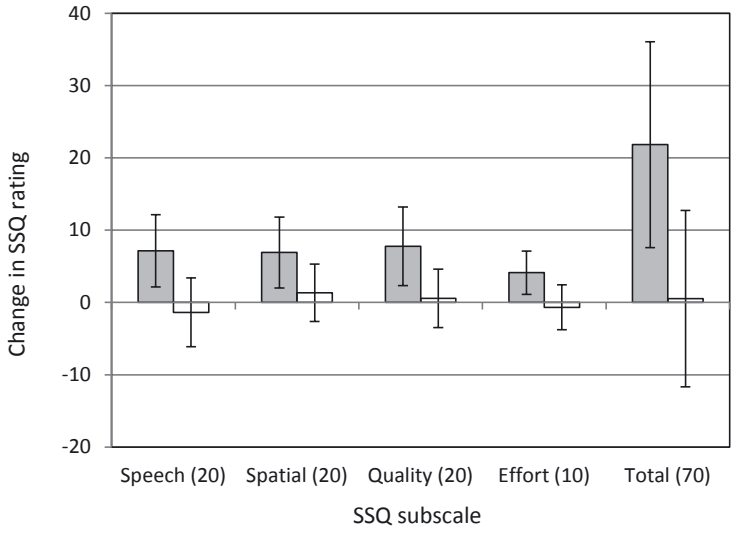

Fig. 1: Changes in self-rated hearing-aid performance over 12 weeks from first fitting, based on the Spatial, Speech and Qualities of Hearing Questionnaire (Gatehouse and Noble, 2004). Experienced hearing-aid users (control group), open columns; New hearing-aid users, filled columns. Positive values represent improvement and values in brackets display the maximum score for each subscale. Error bars show ±1 standard deviation.

study was statistically powered to detect changes of the size reported by previous acclimatization studies. However, as with previous studies, there was wide variability in outcome between participants, and this may obscure small average acclimatization effects. Our conclusion was that if they do exist, acclimatization effects with non-linear hearing aids are probably too small to be of clinical relevance (at least for older adult first-time hearing-aid users and for the outcome measures used in our studies). Despite our null findings with non-linear hearing aids and despite the controversy in the literature concerning the rate, extent and clinical significance of the acclimatization effect, there remains some evidence that a deprived auditory system may be modified by experience with hearing-aid use.

CHANGES INDUCED BY SHORT-TERM SOUND TREATMENTS

The previous section described studies involving adults with age-related hearing loss whereas this section involves studies using normal-hearing participants. The participants were provided with a short-term monaural sound treatment: either an earplug or a low-gain hearing aid. The measures used in the studies include the middle-ear muscle reflex and categorical loudness ratings. Measurements were made at baseline and within 1-2 weeks of commencing the treatment.

The middle-ear reflex is a brainstem reflex that involves bilateral contraction of the middle-ear muscles in response to a high sound level presented to either ear (Borg, 1973). In order to measure the acoustic reflex threshold (ART), short sound stimuli were initially presented below threshold and increased in intensity until there was a repeatable decrease in compliance ≥ 0.02 cm^3.

Loudness judgements were obtained using the Contour Test of Loudness Perception (Cox *et al.*, 1997). Listeners used a response pad to assign one of seven loudness categories to a train of tones. The exact details varied between studies but generally involved initially presenting tones close to hearing threshold. After the listener allocated a loudness category to the stimulus, the presentation level was increased in 5-dB steps and the process repeated until a response was recorded at the highest category, i.e., uncomfortably loud.

In our first study (Munro and Blount, 2009) 11 normal-hearing listeners were asked to use a monaural earplug continuously for 7 days. When hearing levels were measured with the earplug inserted, thresholds showed a mean increase of 22 dB at 0.25 kHz and 46 dB at 8 kHz. After seven days of earplug use, the level of a 2-kHz and 4-kHz tone required to elicit the acoustic reflex in the ear with the earplug had decreased by 5-7 dB, relative to pre-earplug levels. Measurements made 7 days after removing the earplug showed that the ART had returned to baseline values.

In our next study (Maslin *et al*., 2013a), a new group of 11 normal-hearing listeners wore a monaural earplug continuously for seven days. The mean attenuation of the earplug, measured using real-ear insertion gain (REIG), i.e., the difference in response between the plugged and unplugged conditions, was < 10 dB at 0.25 kHz to > 30 dB at 3 and 4 kHz. Whereas Munro and Blount tested acoustic reflexes with two high-frequency stimuli an octave apart, in this study reflexes were tested with a high (4 kHz) and a low (0.5 kHz) frequency pure tone to elicit the reflex. The hypothesis was that a greater decrease in the ART should be observed for higher frequency stimuli because ear plugging provided greater attenuation of input for high frequencies. We found that the level required to elicit an acoustic reflex in the treatment ear decreased by 3 dB at 0.5 kHz and by 7 dB at 4 kHz but the difference between frequencies was not statistically significant.

Munro and Blount (2009) and Maslin *et al*. (2013a) only measured acoustic reflexes so it is unknown if there is a relationship between any changes in perceived loudness and changes in ART. Our most recent study (Munro et al., submitted) addressed this issue. We provided 18 normal-hearing participants with a monaural earplug for 7 days. ARTs were measured with a high (2 kHz) and low (0.5 kHz) frequency tone and with broadband noise. Categorical loudness ratings were obtained at 0.5 kHz and 2 kHz. All measurements were made at baseline and after 7 days use. Further measurements were taken 1 and 7 days after removal of the earplug in order to characterise the time course of recovery. After 7 days of unilateral auditory deprivation, acoustic reflexes were obtained at a lower sound pressure level in the ear that had been fitted with an earplug and at a higher sound pressure level in the not-fitted control ear. In contrast, stimuli were reported as louder after earplug

experience in both ears. The relationship between changes to the ART and changes in loudness was not statistically significant. For both ARTs and loudness, changes had essentially disappeared within 24 hours of earplug removal and this is consistent with homeostatic plasticity (see later).

In our final study, Munro and Merrett (2013) provided 21 normal-hearing listeners with a monaural hearing aid that provided a REIG of 20 dB at 2-4 kHz. ARTs were measured with a 2-kHz and 0.5-kHz pure tone and with broadband noise. After five days of hearing aid use, ARTs were elicited with a higher sound pressure level of 3-4 dB at both 0.5 and 2 kHz, relative to the pre-treatment baseline. The changes occurred in the opposite direction to those reported after sensory deprivation, and this is consistent with experience-driven auditory plasticity. On the categorical loudness task, stimuli were reported as less loud after hearing-aid use but the relationship with changes to the ART was not statistically significant.

Our studies investigating short-term sound treatments provide evidence of plasticity in the adult human auditory system. This plasticity may be explained by a gain control mechanism mediated by a process operating at the level of the brainstem, although this could be controlled from higher levels. A potential function of this gain control mechanism could be to counteract changes in input in order to stabilize the overall level of neuronal activity in the central auditory system. This would require an increase in gain after deprivation and a decrease in gain after additional stimulation, as observed by the changes in sound level required to elicit an acoustic reflex. The lack of relationship between changes in ARTs and loudness, and the different pattern of findings with each measure, suggests multiple gain mechanisms.

The mechanism underlying the changes in ARTs is unknown, but a reasonable candidate is homeostatic plasticity which is thought to stabilize the mean activity of the neuron (Turrigiano, 1999). In response to sensory deprivation, the strength of excitatory synapses is scaled up and the strength of inhibitory synapses is scaled down, resulting in increased neural response gain, which could lead to lower ART thresholds. Conversely, in response to sensory stimulation, the strength of the excitatory synapses is scaled down and the strength of the inhibitory synapses is scaled up, resulting in decreased neural gain, possibly increasing ARTs.

The findings of these studies may have implications for some patients with tinnitus and/or sound tolerance problems. Computational models have illustrated how auditory deprivation may result in an increase in neural gain as homeostatic plasticity attempts to restore average neuronal activity (Schaette *et al.*, 2012). Tinnitus, the perception of a sound in the absence of a corresponding sound source, may be a side-effect of ‘over-amplification’ of spontaneous neural activity due to increased neuronal gain. Likewise, increased gain could cause an ‘over-amplification’ of stimulus-evoked neural activity, leading to sound tolerance problems. This would support the use of sound treatments to ‘reset’ gain.

CHANGES INDUCED BY PROFOUND UNILATERAL DEAFNESS

The studies in the previous sections describe the effect of environmental modification of auditory input via hearing aids or earplug manipulations. The current section refers to the effect of profound unilateral deafness on auditory processing in adult humans. The studies all have the same basic design: The pattern of auditory activity to stimulation of the intact ear is compared (i) before and after the onset of unilateral deafness, or (ii) with that of control participants receiving monaural stimulation. The outcome measures were CAEPs and ABRs.

Normally, stimulation of one ear produces a bilateral but asymmetrical activation within the central auditory system. This is because the ascending contralateral pathway contains more nerve fibres and fewer synapses. However, after unilateral deafness the hemispheric asymmetry disappears as the nerve fibres previously innervated by the deafened ear adapt to become more sensitive to the remaining, intact ear. What is puzzling is that, while this change has consistently been shown in animal models (for review see Moore and King, 2004), the evidence in humans has been less consistent. Studies using fMRI have demonstrated reduced hemispheric asymmetries in humans (e.g., Scheffler *et al.*, 1998; Langers *et al.*, 2005), although those using CAEPs (or CAEFs) have not (e.g., Vasama *et al.*, 2001; Hine *et al.*, 2008). This led us to suspect that there was some aspect of CAEP/Fs methodology, e.g., calculation of hemispheric asymmetries, that could be causing the inconsistency. Our first study compared CAEPs from 18 individuals with unilateral deafness to 18 controls (Maslin *et al.*, 2013b). We focused on the N1 response and measured the asymmetry using Dipole Source Analysis. We controlled for more variables than previous studies. The results revealed an overall increase in the amplitude of N1, and a reduction in the normally observed hemispheric asymmetry.

Individuals due to undergo translabyrinthine surgery (for removal of a unilateral acoustic neuroma) provide an opportunity to study the time course of injury-induced plasticity. Baseline readings from the intact ear can be obtained in advance of the surgery-induced profound unilateral deafness. We have monitored the time course of changes in N1 (and P1 and P2) in five adults from baseline pre-surgery through to 36 months post-surgery (Maslin *et al.*, 2013c; Maslin *et al.,* in prep.). The results showed that even at baseline some changes had already taken place in comparison to the control group, presumably because of some hearing loss in the tumour ear. However, a series of further changes in all three cortical components could be observed post-surgery. The P1 was significantly different to baseline at 1 month post-surgery, whereas changes in N1 and P2 did not reach statistical significance until 6 months post-surgery. Recent data at 36 months post-surgery do not appear to show any further significant changes. The time-course of changes after surgery suggests a range of physiological mechanisms: Some are relatively fast acting (at least within 1 month), and others are more gradual (6 months). Candidate mechanisms include functional disinhibition (i.e., removal of inhibitory input normally acting on the intact ear) and up-regulation of existing synapses and proliferation of new synapses favouring the input from the intact ear.

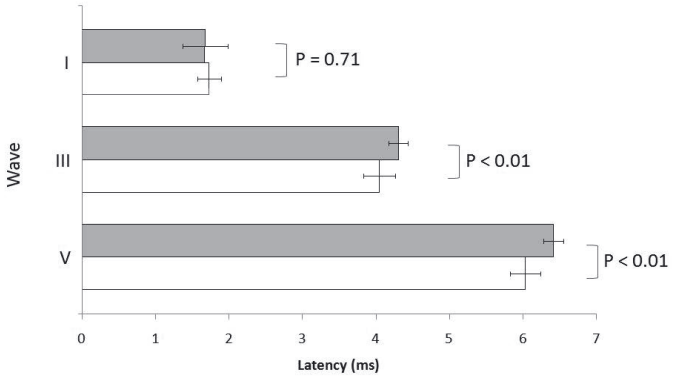

Fig. 2: Mean latencies of waves I, III, and V of the ABR from 7 individuals pre- (filled) and post-labyrinthectomy (open). Error bars show ±1 standard deviation.

Our most recent study has focussed on identifying when the surgery-induced changes can be first measured (Maslin *et al.,* in prep.). Very rapid changes may occur if the physiological mechanism is disinhibition or rapid intra-cellular signalling. We have been conducting ABR measures during surgery. ABRs are unaffected by anaesthesia, and have the added bonus of providing sub-cortical information. The results showed a rapid (within minutes) reduction in ABR latencies for waves III and V post-labyrinthectomy. So far, we have measured responses from seven individuals (see Fig. 2) and are in process of completing testing on control subjects undergoing non-auditory neurosurgery.

Further work is needed to elucidate the perceptual consequences of the physiological changes such as improvements in localisation (Slattery and Middlebrooks, 1994). It is also possible that the physiological changes result in maladaptive changes including tinnitus and hyperacusis. Hence it may be clinically relevant to understand, and potentially manipulate, injury-induced plasticity for therapeutic gain.

CONCLUSIONS

Despite the controversy in the literature concerning the rate, extent, and clinical significance of the acclimatization effect, there is evidence that the deprived auditory system of some listeners can be modified with hearing-aid experience. The findings from our studies involving short-term monaural sound treatments provide evidence of plasticity in the adult human auditory system and are consistent with a neural gain control mechanism. These studies, along with the more extreme example of profound unilateral deafness, may shed light on the underlying mechanisms

causing aberrant auditory perceptions such as tinnitus and hyperacusis, as well as the capacity of the adult auditory system to recover function. Our current studies aim to identify the potential benefits of plasticity.

ACKNOWLEDGEMENTS

Many of the hearing-aid acclimatisation studies were funded by the Starkey Hearing Research Centre. The work was facilitated by the Manchester Biomedical Research Centre, and a Studentship from the Medical Research Council.

REFERENCES

Arlinger, S., Gatehouse, S., Bentler, R.A., Byrne, D., Cox, R.M., Dirks, D., Humes, L.E., Neuman, A., Ponton, C., Robinson, K., Silman, S., Summerfield, A.Q., Turner, C.W., Tyler, R.S., and Willott, J F. (**1996**). "Report of the Eriksholm workshop on auditory deprivation and acclimatization," Ear Hearing, **17**, 87S-90S.

Bentler, R.A., Neibuhr, D.P., and Getta, J.P. (**1993**). "Longitudinal study of hearing aid effectiveness. I Objective measures," J. Speech Lang. Hear. Res., **36**, 808-819.

Bertoli, S., Probst, R., and Bodmer, D. (**2011**). "Late auditory evoked potentials in elderly long-term hearing-aid users with unilateral or bilateral fittings," Hear. Res., **280**, 58-69.

Borg, E. (**1973).** "On the neural organisation of the acoustic middle ear reflex," Brain Res., **49**, 101-123.

Cox, R.M., Alexander, G.C., Taylor, I.M., and Gray, C.A. (**1997**). "The contour test of loudness perception," Ear. Hearing, **18**, 338-400.

Dawes, P., Munro, K.J., Kalluri, S., and Edwards, B. (**2013a**). "Unilateral and bilateral hearing aids, spatial release from masking and auditory acclimatization," J. Acoust. Soc. Am., **134**, 596-606.

Dawes, P., Munro, K.J., Kalluri, S., and Edwards, B. (**2013b**). "Brainstem processing following unilateral and bilateral hearing-aid amplification," NeuroReport, **24**, 271-275.

Dawes, P., Munro, K.J., Kalluri, S., and Edwards, B. (**submitted**). "Hearing aid use-related auditory acclimatization: Late auditory evoked potentials and speech recognition following unilateral and bilateral hearing-aid amplification", J. Assoc. Res. Oto.

Dawes, P., Munro, K.J., Kalluri, S., and Edwards, B. (**in press**). "Acclimatization to hearing aids," Ear Hearing.

Gatehouse, S. (**1989**). "Apparent auditory deprivation effects of late onset: The role of presentation level," J. Acoust. Soc. Am., **86**, 2103-2106.

Gatehouse, S. (**1992**). "The time course and magnitude of perceptual acclimatization to frequency responses: Evidence from monaural fitting of hearing aids," J. Acoust. Soc. Am., **92**, 1258-1268.

Gatehouse, S., and Noble, W. (**2004**). "The Speech, Spatial and Qualities of Hearing Scale (SSQ)," Int. J. Audiol., **43**, 85-99.

Gatehouse, S., and Robinson, K. (**1996**). "Acclimatization to monaural hearing aid fitting – effects on loudness functions and preliminary evidence for parallel electrophysiological and behavioural effects," in *Psychoacoustics, Speech and Hearing Aids*. Edited by B. Kollmeier (World Scientific, Singapore), pp. 319-330.

Hine, J., Thornton, R., Davis, A., and Debener, S. (**2008**). "Does long-term unilateral deafness change auditory evoked potential asymmetries?," Clin. Neurophysiol., **119**, 576-586.

Langers, D.R., van Dijk, P., and Backes, W.H. (**2005**). "Lateralization, connectivity and plasticity in the human central auditory system," Neuroimage, **28**, 490-499.

Maslin, M.R.D., Munro, K.J., Lim, V.K., Purdy, S.C., and Hall, A.D. **(2013a)**. "Investigation of cortical and sub-cortical plasticity following short-term unilateral auditory deprivation in normal hearing adults," NeuroReport, **24**, 287-291.

Maslin, M.R., Munro, K.J., and El-Deredy, W. (**2013b**). "Source analysis reveals plasticity in the auditory cortex: evidence for reduced hemispheric asymmetries following unilateral deafness," Clin. Neurophysiol., **124**, 391-399.

Maslin, M.R., Munro, K.J., and El-Deredy, W. (**2013c**). "Evidence for multiple mechanisms of cortical plasticity: A study of humans with late-onset profound unilateral deafness," Clin. Neurophysiol., **124**, 1414-1421.

Moore, D.R., and King, A.J. (**2004**). "Plasticity of binaural systems," in *Springer Handbook of Auditory Research*. Edited by T.N. Parks, E.W. Rubel, R.R. Fay, and A.N. Popper (Springer-Verlag, New York), pp. 96-172.

Munro, K.J., and Lutman, M.E. (**2003**). "The effect of speech presentation level on measurement of auditory acclimatization to amplified speech," J. Acoust. Soc. Am., **114**, 484-495.

Munro, K.J., Pisareva, N.Y., Parker, D.J., and Purdy, S.C. (**2007**). "Asymmetry in the auditory brainstem response following experience of monaural amplification," NeuroReport, **18**, 1871-1874.

Munro, K.J. (**2008**). "Reorganization of the adult auditory system: Perceptual and physiological evidence from monaural fitting of hearing aids," Trends Ampl., **12**, 254-271.

Munro, K.J., and Blount, J. **(2009)**. "Adaptive plasticity in brainstem of adult listeners following earplug-induced deprivation (L)," J. Acoust. Soc. Am., **126**, 568-571.

Munro, K.J., and Merrett, J.F. **(2013)**. "Brainstem plasticity and modified loudness following short-term use of hearing aids," J. Acoust. Soc. Am., **133**, 343-349.

Munro, K.J., Turtle, C., and Schaette, R. (**submitted**). "Sub-cortical plasticity and modified loudness following short-term unilateral deprivation: evidence of multiple neural gain mechanisms within the auditory system," J. Acoust. Soc. Am.

Palmer, C.V., Nelson, C.T., and Lindley, G.A. (**1998**). "The functionally and physiologically plastic adult auditory system," J. Acoust. Soc. Am. **103**, 1705-1721.

Ramachandran, V.S., Stewart, M., and Rogers-Ramachandran, D.S. (**1992**). "Perceptual correlates of massive cortical reorganization," Neuroreport, **3**, 583-586.

Reber, M.B., and Komopis, M. (**2005**). "Acclimatization in first-time hearing aid users using three different fitting protocols," Auris Nasis Larynx, **32**, 345-351.

Saunders, G.H., and Cienkowski, K.M. (**1997**). "Acclimatization to hearing aids," Ear Hearing, **18**, 129-139.

Schaette, R., Turtle, C., and Munro K.J. (**2012)**. "Reversible induction of phantom auditory sensations through simulated unilateral hearing loss," PLos ONE, **7**, e35238.

Scheffler, K., Bilecen, D., Schmid, N., Tschopp, K., and Seelig, J. (**1998**). "Auditory cortical responses in hearing subjects and unilateral deaf patients as detected by functional magnetic resonance imaging," Cereb. Cortex, **8**, 156-163.

Slattery, W.H., 3rd, and Middlebrooks, J.C. (**1994**). "Monaural sound localization: acute versus chronic unilateral impairment," Hear. Res., **75**, 38-46.

Taylor, K.S. (**1993**). "Self-perceived and audiometric evaluations of hearing aid benefit in the elderly," Ear Hearing, **14**, 390-394.

Turner, C.W., Humes, L.E., Bentler, R.A., and Cox, R.M. (**1996**). "A review of past research on changes in hearing aid benefit over time," Ear Hearing, **17**, 14S-25S.

Turner, C.W., and Bentler, R.A. (**1998**). "Does hearing aid benefit increase over time?" J. Acoust. Soc. Am., **104**, 3673-3674.

Turrigano, G.G. (**1999**). "Homeostatic plasticity in neuronal networks: the more things change, the more they stay the same," Trends Neurosci., **22**, 221-227.

Vasama, J.P., Marttila, T., Lahin, T., and Makela, J.P. (**2001**). "Auditory pathway function after vestibular schwannoma surgery," Acta Oto-Laryngologica, **121**, 378-383.

Weir Mitchell, S., (**1871**). "Phantom Limbs," Lippincott's Mag., **8**, 563-569.

Yang, T.T., Gallen, C., Schwartz, B., Bloom, F.E., Ramachandran, V.S., and Cobb, S. (**1994**), "Sensory maps in the human brain," Nature, **368**, 592-593.