

**Unilateral and bilateral hearing aids, spatial release from masking and auditory  
acclimatization**

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**Abstract**

Spatial release from masking (SRM) was tested within the first week of fitting and after 12 weeks hearing aid use for unilateral and bilateral adult hearing aid users. A control group of experienced hearing aid users completed testing over a similar time frame. The main research aims were i) to examine auditory acclimatization effects on SRM performance for unilateral and bilateral hearing aid users, ii) to examine whether hearing aid use, level of hearing loss, age or cognitive ability mediate acclimatization, and iii) to compare and contrast the outcome of unilateral versus bilateral aiding on SRM. Hearing aid users were tested with and without hearing aids, with SRM calculated as the 50% speech recognition threshold advantage when maskers and target are spatially separated at  $\pm 90^\circ$  azimuth to the listener compared to a co-located condition. The conclusions were i) on average there was no improvement over time in familiar aided listening conditions, ii) there was large test-retest variability which may overshadow small average acclimatization effects; greater improvement was associated with better cognitive ability and younger age, but not associated with hearing aid use, iii) overall, bilateral aids facilitated better SRM performance than unilateral aids.

## I. Introduction

Complex auditory environments with multiple sources of noise pose a great challenge to listening, especially for hearing impaired individuals. Listeners experience benefit in speech intelligibility in such complex listening conditions if target and noise sources are spatially separated (Yost, 1997; Bronkhorst, 2000; Ebata, 2003). The benefit of spatial separation is experimentally quantified by the difference between performance when target and interferer are separated and performance when target and masker are co-located, with this quantity referred to as 'spatial release from masking' (SRM). The size of the benefit can be several decibels (dB) depending on listening conditions. Auditory acclimatization (truncated to "acclimatization" from here on) refers to an improvement in aided listening over time as the hearing aid user learns to make optimal use of auditory cues made audible by the hearing aid. This improvement is not due to practice or test-retest effects, but is a form of perceptual learning (Arlinger *et al.*, 1996). Given that hearing aids alter binaural cues via restoration of high frequency input and potentially introduce time delays and spectral distortions, one might expect that a period of acclimatization might be necessary in order to adjust to altered binaural cues. Additionally, if it were the case that novice hearing aid users were poor at making use of cues for spatial separation at initial fitting and improved with acclimatization, it may be possible to speed the acclimatization process through training and improve benefit from hearing aids, particularly in complex and noisy acoustic environments (Sweetow and Palmer, 2005). The primary aims of the present study were i) to test whether there are auditory acclimatization effects on SRM for new-unilateral and bilateral hearing aid users, compared to a control group of experienced hearing aid users, ii) to test whether hearing aid use, level of hearing loss, age or cognitive ability mediate SRM acclimatization

and iii) to compare and contrast the outcome of unilateral versus bilateral aiding on SRM, following a period of acclimatization.

#### **A. Spatial release from masking**

SRM depends upon differences in the auditory signal reaching the two ears. The two primary cues are 1) interaural timing differences (ITDs) and 2) interaural level differences (ILDs) (Moore, 2004). ITDs are thought to be most significant for frequencies below 1.5 kHz, with ILDs most effective for frequencies above 1.5 kHz. Older listeners may experience reduced SRM in complex, naturalistic listening situations for three reasons; 1) reduced availability of ILD cues through loss of audibility of high frequency sounds (Dubno *et al.*, 2002), 2) reduced ability to benefit from fluctuations in the intensity and frequency composition of the interfering noise through loss of temporal and spectral resolution (Peissig and Kollmeier, 1997), and 3) reduced ability to selectively attend to the signal of interest within an auditory scene because of reduced cognitive ability (Neher *et al.*, 2011).

Hearing aids restore audibility of high frequencies to some extent, and so one might expect that SRM would be improved as high frequency-dependent ILD cues are restored. In general the data show that aided SRM is better than unaided SRM, though performance remains below the level of normally hearing listeners (Festen and Plomp, 1986; Marrone *et al.*, 2008; Ahlstrom *et al.*, 2009). One potential reason for this is that although audibility is at least partially restored, hearing impaired listeners' performance may still be limited by reduced temporal and spectral resolution, which may not be ameliorated by hearing aids. For older listeners, reduction in cognitive capacity may also be a factor. Additionally, hearing aids may introduce distortions that affect both ILD and ITD cues. For example, bilateral hearing aids are typically fitted so that they operate independently across ears; directional microphones,

noise reduction and compression schemes are applied independently, introducing time delays and spectral distortions that can disrupt binaural performance (Keidser *et al.*, 2006; Van den Bogaert *et al.*, 2006). For behind-the-ear (BTE) hearing aids, microphone position also has a disruptive effect (Festen and Plomp, 1986; Best *et al.*, 2010). There is some evidence, however, that listeners can acclimatize to altered binaural cues (Drennan *et al.*, 2005; Keidser *et al.*, 2006), and this is reviewed as follows.

### **B. Auditory acclimatization and SRM**

Recommendations concerning consistent hearing aid use and acclimatization are commonly made in clinical practice, and acclimatization periods are routinely used in hearing aid research. Most acclimatization research has focused on speech recognition in noise and loudness perception (see reviews by Munro, 2008; Palmer *et al.*, 1998 and Turner *et al.*, 1996). For example, Gatehouse (1992) and subsequently Munro and Lutman (2003) found improvement of speech recognition in the fitted ear relative to that in the non-fitted ear after weeks of monaural hearing aid use in adults with symmetrical bilateral hearing loss. Gatehouse (2003) further showed that the benefit of re-fitting experienced hearing aid users with a theoretically more advantageous frequency response was only evident after several weeks of experience.

Research on SRM and acclimatization by hearing aid users is sparse. The only study that we are aware of that examined SRM and acclimatization in hearing aid users is that of Drennan *et al.* (2005). Drennan *et al.* examined changes in SRM for speech in noise in bilateral hearing aid users. Participants, fitted bilaterally with hearing aids, showed improvement of SRM (by 2% to 4%) with 16 weeks of experience. This study provides perhaps the most compelling evidence that acclimatization effects for SRM do occur for hearing aid users.

However, no control group was utilised and so the apparent improvements may have been at least partially due to re-test effects rather than acclimatization. Also, the sample size was small ( $N = 7$ ), and users were experienced hearing aid users, which may have resulted in any acclimatization effects being smaller than those observable in novice users.

As with the use of spatial separation for improving the intelligibility of speech in noise, auditory localisation also depends largely upon utilisation of binaural cues. Several studies have examined acclimatization effects for sound localization. Drennan et al (2005), discussed above, found modest improvements in localisation accuracy (5 to 10 degrees reduction in RMS errors) with three or more weeks of experience. In another study, participants tended to do poorly on a localisation task with HA styles (BTE, in-the-ear (ITE) or in-the-canal (ITC)) that differed from their usual one (Noble and Byrne, 1990). The interpretation was that participants had not acclimatized to the input provided by the different style aid. Two other studies have reported improvements in hearing aid users' localisation abilities over a period of several weeks following fitting with new hearing aids (Keidser *et al.*, 2006; Best *et al.*, 2010). Both studies concluded that improvements in localisation were due to acclimatization. However, both studies used relatively small samples and had no control group, and so one cannot rule out the possibility that improvements may have been due to test-retest effects.

Changes in localisation abilities of normally hearing participants following unilateral ear-plugging, which would potentially disrupt binaural cues, are also informative about acclimatization effects in binaural hearing. In an early study Bauer, Matuzsa and Blackmer (1966) gave normally hearing participants a unilateral ear plug, and found that their localisation abilities normalised within 1-3 days. Numerous subsequent studies have

supported conclusions that localisation may improve following alteration of cues and that training may increase localisation performance (reviewed by Wright and Zhang, 2006).

Evidence for acclimatization effects in binaural hearing also come from measurements of Binaural Masking Level Difference (BMLD) in those with unilateral conductive hearing loss. The BMLD refers to the use of inter-aural difference cues to aid detection of tonal stimuli (Hirsh, 1948; Licklider, 1948). Magliulo *et al.* (1990) and Hall and Grose (1993) measured the BMLD in participants longitudinally following corrective surgery for unilateral conductive hearing loss. Both studies found that for some participants the BMLD continued to improve over time. The suggestion was that unilateral conductive hearing loss had resulted in a lack of binaural stimulation and caused deprivation effects. This impacted upon the BMLD such that a period of experience with normal bilateral stimulation was required in order to relearn cues for the BMLD.

In summary, SRM may improve over time as new hearing aid users acclimatize to altered binaural cues, although no study has examined this directly to date. Significant SRM acclimatization effects could have implications for hearing aid counselling and may suggest an opportunity for increasing hearing aid benefit via specific SRM training to boost acclimatization.

### **C. Predictors of Acclimatization**

One noted feature of previous acclimatization research is variability of outcome; some participants show improvements in aided performance over time while others do not (Turner *et al.*, 1996). Factors such as the amount of hearing aid use, degree of hearing loss, age and cognitive capacity may explain the variability (Tyler and Summerfield, 1996; Palmer

*et al.*, 1998). With regard to hearing aid use, if acclimatization depends on regular experience with novel auditory input, this would require consistent hearing aid use. With respect to the degree of hearing loss, Palmer et al (1998) identified that studies that have not detected acclimatization effects tended to include participants with relatively mild losses. They suggested that only when high-frequency losses exceed 40-45 dB HL would significant loss of input from conversational levels of speech be experienced, and thus there would be greater likelihood of acclimatization once input was restored. Palmer et al. (1998) also speculated that decreases in neural activity and weaker synaptic strength with age may have an adverse impact upon acclimatization. With respect to cognitive factors, Tyler and Summerfield (1996) suggested that acclimatization may involve extraction of speech cues from novel patterns of input, associating those cues with stored representations of speech and language and redefining stored representations as necessary. This conception sees acclimatization as a cognitively demanding process, and so cognitive ability may also be a constraining factor in acclimatization.

#### **D. Aims**

This study presents three sets of analyses addressing three aims:

1). In order to test for auditory acclimatization effects on the ability to use spatial separation for improving intelligibility of speech in noise for unilateral and bilateral hearing aid users, SRM was determined for two conditions. i) A linear-gain listening condition (where linear gain was applied at the loudspeaker to compensate for each listener's degree of hearing loss) in order to circumvent any distortion of cues introduced by the hearing aids, and ii) aided listening configurations. New-unilateral and new-bilateral hearing aid users were tested. It was hypothesised that specific improvements would be seen in the aided listening



configuration that matched the new-users' usual daily listening configuration (the "familiar listening" condition). In other words, unilateral users would show specific improvements for unilateral aided SRM, but only for the side that was their familiar aided side, while bilateral users would show improvements in bilateral aided SRM. As improvement may occur in all listening conditions due to test-retest effects, a control group of experienced hearing aid users was included.

2). In order to examine whether hearing aid use, level of hearing loss, age or cognitive ability mediate acclimatization, correlations between these variables and the change in the "familiar" aided condition and the linear gain condition were obtained. The hypothesis was that improvements in SRM in the familiar aided condition would be associated with more consistent hearing aid use, more severe hearing loss, younger age, higher working memory capacity and faster speed-of-processing. However, if predictors were associated with improvements in SRM for linear-gain listening conditions, this might suggest that they were of more importance for generalised procedural learning across conditions, rather than to acclimatization specifically related to hearing aid use.

3). In order to compare and contrast the outcome of unilateral versus bilateral aiding on SRM, unilateral versus bilateral SRM were compared. In order to describe the constraints on SRM, the effect of hearing loss and cognitive ability on SRM was examined while controlling for age.

## **II. Methods**

### **A. Participants**

A total of 48 experienced and novice hearing aid users were recruited from four local audiology clinics in Manchester, UK, and ethics approval obtained from the appropriate bodies and informed written consent obtained from participants. Sample size was determined on the basis of number of participants required to provide 80% statistical power to detect a clinically important difference of 2 dB change in SRM, given a standard deviation of 2 dB and using a two-tailed repeated measures t-test with an alpha level of 0.05. The estimate of standard deviation was based on the data of Marrone et al. (2008) and on piloting of the present paradigm with young normally hearing volunteers. The computed sample size was  $n = 10$ . Nevertheless, as it was suspected that older, hearing impaired participants may have greater variability of performance than the young normally hearing volunteers with whom the task was piloted, the sample size estimates were treated conservatively and somewhat larger group sizes were actually used ( $n = 17, 16$  and  $15$ ).

The main inclusion criterion was symmetrical, mild-to-moderate, sloping high frequency sensorineural hearing loss of at least 40 dB at each frequency between 2–6 kHz. The exclusion criteria were i) fluctuating or recent changes in hearing level, ii) asymmetry in air conduction thresholds of greater than 15 dB at any two or more frequencies between 0.25 and 6 kHz, iii) an air–bone gap greater than 15 dB at any test frequency, iv) abnormal middle ear function assessed using oto–admittance audiometry. Additional inclusion criteria for experienced hearing aid users was a minimum of one year’s hearing aid use and self reported daily hearing aid use of at least six hours per day, and for new-users a history of hearing loss of at least one year duration (based on self report) and no prior hearing aid use.

Thirty-three new-users were recruited, with 17 users being fit unilaterally and 16 fit bilaterally. Allocation to unilateral or bilateral fitting was made as the participants were

recruited to the study, alternating between unilateral and bilateral fitting. No participant expressed a strong preference for or against unilateral or bilateral aiding, and unilaterally fit participants had the option of changing to bilateral aiding on completion of the study, and vice versa. Fifteen experienced-users were recruited, including seven bilateral and eight unilateral hearing aid users.

The mean audiometric thresholds by frequency for left and right ears (measured at entry to the study) for each ear is displayed in Fig. 1. The mean hearing thresholds (taken as the average threshold for 0.5, 1, 2 and 4 kHz across both ears) were 39 dB HL (s.d. = 7; range 27 to 43 dB HL), 39 dB HL (s.d. = 6; range 32 to 45 dB HL) and 46 dB HL (s.d. = 11; range 29 to 61 dB HL) for the new-unilateral, new-bilateral and experienced-user groups, respectively. Hearing thresholds were retested at around 12 weeks later at the end of the study. The mean change in threshold across frequencies and groups was 0.2 dB (s.d. = 2.6 dB): 80% of hearing thresholds changed by less than 5 dB, which is in line with reported test-retest differences for audiometry (Robinson, 1991). The mean age of each group was 69 (s.d. = 10; range 48 to 84), 67 (s.d. = 12; range 45 to 84) and 73 (s.d. = 7; range 64 to 90) years for the new-unilateral, new-bilateral and experienced-user groups, respectively. The experienced-user group tended to be older and have slightly poorer hearing on average than the new-user groups.

(Figure 1 here)

### **B. Amplification, fitting and electroacoustic measures**

Hearing aid gain was verified using real ear measures at the start of the study to ensure that gain was being provided at levels close to NAL-NL1 (Dillon *et al.*, 1998) prescribed levels.

Maximum output was determined with reference to loudness discomfort level obtained

during initial assessment and adjusted if the participant reported any undue discomfort.

Hearing aid gain was re-measured at the end of the study to ensure that no changes in gain could account for any changes in SRM performance. Fig. 2 shows the mean real ear insertion gain (REIG) and REIG as worn by the user for an input of 65 dB SPL. The mean change in REIG between T1 and T2 was -0.7 dB (i.e. less gain over time, s.d. = 1.9). The difference is likely due to test-retest variability.

The new-users' hearing aids were either Starkey Radius behind-the-ear with vented skeleton ear mould (BTE; n = 7) or Starkey Destiny completely-in-the-canal (CIC; n = 26) aids<sup>1</sup>. Both BTE and CIC aids contain identical hardware and signal processing. They had an 8-channel compressor, with gain adjustable in twelve bands, and noise management was activated. Compression in these hearing aids operated with an attack time of 20 ms and release time of 2000 ms, measured per the ANSI S3.22 standard. Adaptive listening programs were disabled for the duration of the study. For BTE hearing aids, directional microphones were enabled for daily use and switched to omnidirectional mode for SRM testing following the procedure used by Marrone *et al.* (2008)<sup>2</sup>. For unilateral fittings, the ear of fitting alternated as participants were recruited to the study so that 8 users were fit in the right ear, 9 in the left. (Note that bilateral hearing aids were fitted at T1 for the unilateral users, though one hearing aid was retained in the lab and only used in test sessions). All newly fit participants were allowed at least one day's trial use of the hearing aid, and the gain adjusted if the participant felt they could not tolerate the level of gain as prescribed. No further gain adjustments were made during the study period between T1 and T2, and hearing aids did not have volume controls. Newly fit participants were asked to use their hearing aid(s) at least six hours per day.

Experienced-users continued to use their existing hearing aids with no alterations in hearing aid gain. Their hearing aids were either Danalogic 6070 BTEs ( $n = 7$ ), Oticon Spirit 3 BTEs ( $n = 2$ ), Oticon Synchro CICs ( $n = 2$ ), Oticon Spirit 2 BTE ( $n = 1$ ), Oticon Spirit 3 BTE ( $n = 1$ ), Oticon Spirit Zest ( $n = 1$ ) and Siemens Reflex 1012 ( $n = 1$ ). All of these hearing aids used non-linear processing and had been fit to NAL-NL1 prescription by an audiologist.

(Figure 2 here)

### **C. Test protocol**

All participants received otoscopy, pure tone audiometry, REIG measures and completed the SRM task, on the same day, at the beginning of the experiment (T1). New-users were tested within 7 days of initial fitting (mean = 3 days, s.d. = 2). After around 12 weeks (T2), all participants repeated otoscopy, pure tone audiometry, REIG and the SRM task. The mean time between T1 and T2 was 92 days (s.d. = 17; range 71 to 116 days), with the exact time interval varying depending on the availability of the participant for testing. Testing was carried out in a sound treated audiometric booth containing two chairs, loud speakers, desk, computer and computer monitor with an average reverberation time of 0.1 seconds across 0.125 to 8 kHz. This is slightly more favourable than within an average domestic living room (around 0.3 seconds; Burgess and Utley, 1984). The participant was seated in the centre of the booth, with three loudspeakers positioned at ear level, 1.5 m from the reference test point which was the approximate centre of the listener's head. The loudspeakers were positioned directly in front (at  $0^{\circ}$ ), and to the left and right ( $+90^{\circ}$ , and  $-90^{\circ}$  azimuth) of the participant, with sound levels in 5 dB steps between 40 and 90 dB SPL - covering the range of intensities for target and masker stimuli - for each loudspeaker calibrated at the reference test point. A computer monitor was placed in front of the participant below the

level of the speaker to display task instructions and response options. The SRM task was controlled by a PC computer with M-Audio Fast Track Ultra external sound card and Denon PMA-250111 amplifiers linked to three stand-mounted Tannoy 607 loudspeakers.

#### **D. SRM Task**

##### **1. Stimuli**

The stimuli were Kitterick et al.'s (2010) British accent recordings by four different female speakers of the coordinate response measure (CRM) corpus (Bolia *et al.*, 2000). The corpus contains sentences with the form "Ready (call sign), go to (colour) (number) now". There are eight possible call signs (Baron, Ringo, Charlie, Hopper, Tiger, Laker, Eagle, Arrow), four colours (White, Red, Green, Blue) and eight numbers (1 to 8), with all possible combinations of call sign, colour and number. On each trial, three sentences were presented simultaneously to the participant, each spoken by a different speaker. Sentences and speakers varied from trial to trial. The target sentence (presented at  $0^{\circ}$  azimuth as described below) began with the call sign "Baron". The masker sentences (presented at  $+90^{\circ}$  and  $-90^{\circ}$  azimuth) were spoken by different speakers and contained different call signs, colours and numbers from the target and from each other.

##### **2. Procedure**

A 4x8 alternative forced-choice task was used, similar to that described by Marrone and colleagues (2008). Participants were asked to identify the colour and the number following the call sign "Baron", and told that the target sentence would always be heard from the speaker directly in front of them. A trial began with a visual cue to listen. After stimulus presentation, the participant was required to select the target colour and number combination via mouse click from a closed set of options presented on the computer

monitor. Responses were taken as correct if the listener correctly identified both the target colour and number. No feedback was provided about performance during testing. A one up, one down adaptive procedure was used to estimate the 50% correct point on the psychometric function (Levitt, 1971). Each adaptive track contained at least 10 reversals, corresponding to approximately 30 trials. Initial step size was 4 dB, reducing to 2 dB after the first three reversals. Threshold was calculated based on average of the last 4 reversals, discarding the first six reversals.

Participants were first tested without maskers to establish recognition thresholds with and without their hearing aids. These thresholds were used to set the intensity level of the target in the masked identification conditions: it was equal to recognition threshold (in dB SPL) plus 30 dB. In masked runs, three CRM sentences were presented simultaneously; one target sentence and two masking sentences. The target sentence always occurred at the speaker directly in front of the participant. In the co-located condition, two masker sentences were presented also from the front speaker. In the spatially separated condition, one masker sentence was presented from the speaker at  $+90^{\circ}$  azimuth, the other masker sentence from the speaker at  $-90^{\circ}$  azimuth to the participant. In each condition, the intensity level of the target was fixed (at recognition threshold plus 30 dB) and the level of the two maskers varied adaptively to estimate the 50% correct point on the psychometric function. The two masker sentences were initially presented at -20 dB with respect to the target, with 4 dB steps reducing to 2 dB steps after the first three reversals. Thresholds were calculated from the adaptive track as for the quiet conditions, described above. The SRM was calculated as the difference between the threshold target to masker ratio for the co-

located listening condition and that for the spatially separated condition, so that larger values represent greater benefit in speech recognition from spatial separation.

Participants performed the co-located and the spatially separated tasks in both the linear gain and aided conditions. Except for experienced unilateral hearing aid users, all participants performed left and right unilaterally aided conditions as well as bilaterally aided conditions (as the experienced unilateral users did not have a second matched hearing aid, so only one unilaterally aided listening condition was performed). The order of testing was counterbalanced across participants.

### **E. Age and cognitive measures**

For the present study, two measures of cognitive ability were selected. First, a recent review (Akeroyd, 2008) suggested that working memory capacity is the cognitive skill that is most reliably associated with speech recognition performance, and a model has been proposed with working memory as a key resource for mapping unfamiliar or degraded speech input onto established phonological representations (Ronnberg *et al.*, 2008). Accordingly, working memory was tested in this study and used as a predictor variable for SRM acclimatization. Speed of processing was also tested, and is intended as a general measure of cognitive integrity; associations between speed of processing and other cognitive abilities are so consistent that some investigators have suggested that cognitive declines with aging are due fundamentally to declines in processing speed (Salthouse, 1996).

#### **1. Working memory**

Participants completed the digits backwards subtest from the Wechsler Adult Intelligence Scale-III (Wechsler, 1997). Participants were asked to repeat lists of aurally presented digits



of ever increasing length in reversed sequence and scored correct if all digits are recalled in the correct order. Testing was stopped when two consecutive items were failed.

Participants wore their hearing aids to complete this task. The maximum score was 14.

## **2. *Speed-of-processing***

Reaction times were tested with a paradigm used in a large study of cognitive aging (Deary and Der, 2005). Choice reaction times were recorded in response to four numbers 1-4 presented on a computer monitor, with participants required to press the corresponding key. There were eight practice trials and 40 test trials. In the test trials, each digit appeared 10 times in randomised order. Reaction times in milliseconds and correctness of response were recorded for each test trial. The time interval between a response and presentation of the next digit varied randomly between one and three seconds, and participants were instructed to press the appropriate button 'as quickly as possible'. Reaction times were averaged to provide an overall reaction time measure in milliseconds.

## **F. *Statistical analysis***

All data were assessed for normality of distribution and non-parametric tests applied where appropriate. The changes in performance between T1 and T2 were tested with paired samples t-test (or Wilcoxon signed ranks test, where appropriate). Repeated measures ANOVA was not appropriate in this case because of different numbers of participants across listening conditions and non-normal distributions in some conditions for some groups. One-way ANOVA (or Welch's t-test, where appropriate) was used to test for differences in T1-T2 changes in average SRM between groups. Pearson product-moment correlation coefficients were calculated to establish correlations between predictors of acclimatization and T1-T2 changes in SRM. For examining the constraints of hearing loss and cognitive ability on SRM, partial correlations between SRM and hearing level, reaction time and working memory

were carried out controlling for age. Correlations for co-located and separated performance at T1 and T2 were examined to check for differential associations with predictors; none were detected. These are not reported here.

### III. Results

The unaided speech identification thresholds in quiet for 50% correct criterion performance were 57.1 (s.d. = 9.8), 63.1 (s.d. = 8.0) and 60.4 (s.d. = 13.2) dB SPL for the new-unilateral, new-bilateral and experienced-user groups respectively. The corresponding aided thresholds were 54.5 (s.d. = 6.0), 56.5 (s.d. = 4.7) and 57.2 (s.d. = 8.3) dB SPL, respectively. They were thus lower (better) than unaided by around 1 to 6 dB. Both unaided and aided identification thresholds were correlated with mean audiometric PTA for both ears (Pearson  $r$ 's 0.71 and 0.63, respectively,  $p < 0.001$ ).

#### A. Acclimatization and spatial release from masking

Fig. 3 shows target to masker ratios (TM) at threshold for each masked condition (co-located and spatially separated) as well as spatial release from masking (SRM) for each listening condition at T1 and T2. At T1, the co-located TMs ranged from 1.7 to 4.1 dB, with a trend for poorer performance by about 1 dB in the experienced-user group. For spatially separated TMs, performance ranged from -3.6 to 3.6 dB. Again, there was a trend for poorer performance in the experienced-user group. Within group variability was higher for the spatially separated condition. With the exception of the aided right test condition in experienced-users, there was a benefit associated with spatial separation. The SRMs were similar across groups for the linear-gain listening condition, with a mean of 5.7 dB for all participants across groups, although the mean SRM in unilaterally aided listening conditions

was around 1.5 dB poorer compared to the bilaterally aided listening conditions. The mean aided SRM tended to be poorer in the experienced-user group by around 2 to 4 dB compared with the new-user groups.

At T2, the overall pattern of threshold TM ratios and SRMs was similar to that at T1. The correlations between T1 and T2 SRM scores for all participants were significant ( $p < 0.001$ ), ranging from 0.48 to 0.64 across groups. The mean change in threshold TM ratios between T1 and T2 was small; generally less than 1 dB for the co-located condition and less than 2 dB for the spatially separated condition. The SRMs were also similar between T1 and T2. Significant differences at the level of  $p < 0.05$  are indicated on Fig. 3, though none were statistically significant after Bonferroni correction for multiple comparisons. For all groups, the variability in change in performance was high.

(Figure 3 here)

For the Unilateral group, there was a statistically non-significant mean decrement in SRM of 0.1 dB for the fitted condition. For the New-bilateral group, improvement in the bilateral listening condition was smaller than improvements in unilateral and linear-gain listening conditions. There were no statistically significant T1-T2 changes in average SRM in any aided condition between groups (Fitted/left ear  $F(2,45) = 1.79, p = 0.18$ ; Non-fitted/right ear  $F(2,45) = 2.56, p = .09$ ; Bilateral  $F(2,37) = 0.11, p = 0.90$ ). Significant group differences were apparent for the linear-gain condition, where the new-bilateral user group improved significantly more than the experienced group (Welch  $F(2,26.6) = 3.77, p = 0.04$ ; Fisher's LSD  $p = 0.01$ ), although note that this is partly due to a coincident reduction in linear-gain SRM in the experienced group. Thus on average, the new-user groups did not show any T1-T2

changes in aided SRM relative to the control group of experienced hearing aid users that could be ascribed to acclimatization effects, rather than test-retest effects.

To test for the possibility of early, rapid acclimatization, a new variable was calculated; for new-unilateral participants  $SRM_{\text{Unilateral-fitted side}} - SRM_{\text{Linear-gain}}$ ; for new-bilateral users  $SRM_{\text{Bilateral aided}} - SRM_{\text{Linear-gain}}$ . The values obtained should minimise the effect of individual differences on SRM (for example, due to degree of hearing loss) and emphasise the specific effects of hearing aid amplification on SRM. This variable will be referred to as T1-accl. To test whether early acclimatization occurred, T1-accl was correlated with the number of days between fit and T1 testing for each participant. The correlations were non-significant; Pearson's  $r = -0.27$ ,  $p = 0.30$  for new-unilateral users and  $r = -0.01$ ,  $p = 0.95$  for new-bilateral users. This does not support the possibility that new-users may have acclimatized within the first few days of hearing aid use.

To test for differences in acclimatization between hearing aid styles, new users were grouped by hearing aid style (BTE/CIC) across both new-user groups ( $N = 33$ ). On average there was no statistically significant difference in T1-T2 change in aided SRM in the familiar listening condition between hearing aid styles ( $-1.57$  dB for BTE and  $0.80$  dB for CIC styles,  $t(31) = 1.15$ ,  $p = 0.26$ )<sup>3</sup>.

### **B. Predictors of acclimatization**

For new hearing aid users (unilateral and bilateral groups), the mean amount of hearing aid use (indexed by mean daily hours of use) was 8 hours (s.d. = 3; range 2 to 13). The mean working memory score was 5.9 (s.d. = 1.8, range 3 to 10). The mean reaction time was 791 ms (s.d. = 170, range 532 to 1214). Reaction time was log transformed in order to normalise distribution of scores. Table I reports the correlations between T1-T2 change in SRM over

time for aided and linear gain conditions and predictors of acclimatization. Fig. 4 shows scatter plots of improvement in linear-gain and aided SRM with age and reaction time. The correlation between T1-T2 change in aided SRM and linear-gain SRM was non-significant ( $r = 0.29$ ).

There was no association with any predictor variable and T1-T2 change in linear-gain SRM ( $|r| < 0.26$ ). For T1-T2 change in aided SRM, there was no association between hearing aid use, hearing threshold or working memory ( $|r| < 0.12$ ), but there were significant correlations between T1-T2 change in aided performance and age and reaction time, with younger age and faster reaction time associated with greater improvement over time ( $|r| > 0.35$ ). Note that some changes in both linear-gain and aided SRM are large for certain individuals, up to around 10 dB in some cases, and so intra-individual variability may mask small systematic changes between T1 and T2.

(Table I and Figure 4 here)

### **C. Unilateral versus bilateral aiding**

In order to compare and contrast the outcome of unilateral versus bilateral aiding on SRM, participants were pooled across all three participant groups with T1 and T2 data averaged. There was no statistically significant difference in aided SRM between BTE and CIC users (1.1 dB s.d. = 3.3 versus 1.6 dB s.d. = 2.7  $t(46) = 0.56$ ,  $p = 0.58$ ; 95% CI for the difference -2.2 to 1.3), and so users were grouped across hearing aid styles. There was no significant difference between left and right unilateral aided conditions ( $t(23) = 1.20$ ,  $p = 0.24$ ), and so right and left unilateral aided conditions were averaged to provide a unilateral aided score. Three paired comparisons were then carried out on mean unilateral aided SRM (4.1 dB, s.d. = 4.5), mean SRM for linear-gain (5.5 dB, s.d. = 4.6) and bilaterally aided (6.0 dB, s.d. = 4.4)

conditions<sup>4</sup>. Linear-gain SRM was significantly better than unilateral SRM ( $t(47) = 2.19, p = 0.03$ ; mean difference 1.5 dB, 95% CI 0.1 to 2.9 dB). There was no significant difference between linear-gain and bilateral aided SRM ( $t(39) = 0.72, p = 0.48$ ; mean difference 0.5 dB, 95% CI -1.0 to 2.0 dB). Bilaterally aided SRM was significantly better than unilaterally aided SRM ( $t(39) = 2.80, p = 0.008$ ; mean difference 1.4 dB, 95% CI 0.4 to 2.5 dB).

Table II reports the partial correlations between SRM and hearing level, reaction time and working memory. These calculations were carried out controlling for age. The SRM conditions were strongly correlated with each other ( $|r| > 0.42$ ). There was a medium correlation between working memory and reaction time ( $r = -0.37$ ), with better working memory associated with faster reaction times independent of age. Neither working memory nor reaction time was associated with SRM. Hearing loss (PTA) was correlated with each SRM condition ( $|r| > 0.42$ ), thus hearing loss appears to be the primary determinant of SRM for both aided and linear-gain listening conditions, independent of age.

(Table II here)

#### IV. Discussion

On average there was no evidence of specific improvements in the familiar, 'trained' conditions in the new-user groups which would be consistent with acclimatization, despite a study design that had adequate statistical power to detect changes in SRM that would be clinically relevant. No changes in aided performance in the new hearing aid user groups were statistically significant compared to changes in the experienced-user control group. Thus, there was no evidence of acclimatization effects for SRM, at least on the basis of average performance at the group level.

There are certain limitations to this conclusion however. First, as new hearing aid users were tested within a week of fitting on average, it may have been the case that users had already acclimatized to changed patterns of input within the first few days of hearing aid use, and thus this change would not have been detected in comparing T2 with T1 performance. This possibility of “early acclimatization” was investigated, however, and there was no significant association between aided performance and the number of days after fitting. There was no evidence that new-users acclimatized within the first few days of hearing aid use. There was also no evidence for different sized acclimatization effects for BTE versus CIC style hearing aids, although this comparison was statistically under powered. Additionally, the variability in T1-T2 change in SRM was large, and it may be that the SRM measure itself is unreliable. In fact, although the correlations between the T1 and T2 measures of SRM were highly statistically significant, they were only medium sized in magnitude (0.48 to 0.64), and so acclimatization effects may have been undetectable within this variability. A large variability in outcome is not an unusual finding in acclimatization research (Turner and Bentler, 1998). Some of this variability may be masking acclimatization effects and several explanatory factors have been suggested to explain why some new participants seem to show acclimatization effects, while others do not (Turner *et al.*, 1996; Tyler and Summerfield, 1996; Palmer *et al.*, 1998). Apart from variability in the outcome measures themselves, the amount of hearing aid use, the initial degree of hearing loss, age and cognitive abilities of participants have been suggested as potentially accounting for variation in outcome. If acclimatization depended upon these factors, then more frequent hearing aid use, more severe hearing loss, younger age, larger working memory and faster reaction times would be associated with greater improvements in SRM over time.

Additionally, such correlations would only occur for the familiar listening condition (equivalent to the 'trained' condition), with no correlations with the 'untrained', linear-gain listening condition. Our data showed there were no significant correlations between any predictor variable and change in linear-gain SRM. For the T1-T2 change in the familiar aided listening condition, there was no association with working memory or hearing aid use, although there were correlations with reaction time and age. Younger people and those with faster processing (assumed to be a marker of higher general cognitive capacity) tended to improve more than older people and those with slower processing (i.e. lower cognitive capacity). Age and reaction time correlated strongly with each other, and so the interpretation is that cognitive ability, rather than age per se, is the limiting factor. As to the specific cognitive skill that may constrain acclimatization, there was no association in our data between working memory and improvement in aided SRM over time. We suspect that attention skills are likely to be important for both the use of spatial separation to improve speech reception in noise and acclimatization. Our speech reception task is attentionally very demanding; participants must identify and remain focused on the target phrase while ignoring distracter phrases. Neher et al. (2011) found that speech recognition correlated with attentional ability – but not working memory - in a similar speech reception task to that used in the current study. Interestingly, although improvement in aided SRM depended on cognitive capacity, it was unrelated to the amount of hearing aid use. This seems contrary to the common clinical advice that frequent, consistent hearing aid use will lead to greater benefit.

Bilateral aids resulted in significantly better SRM than unilateral aids on average, though the size of the difference was small (about 1.5 dB), and this is consistent with previous studies



(Festen and Plomp, 1986; Marrone *et al.*, 2008). There was no statistically significant difference between linear-gain and bilateral aided performance, with mean SRMs of 5.4 and 6.0 dB for both conditions. One might have imagined a relative benefit of hearing aids, as they provide amplification specific to those frequencies where hearing loss has occurred. On the other hand, as hearing aids may introduce distortions (e.g. because of behind-the-ear microphone position in BTE aids), they may have a negative impact on performance, relative to the linear-gain condition. The data in the present study suggest that acoustic distortions introduced by hearing aids have a negligible impact on SRM, and this is also in accordance with conclusions by Marrone *et al.* (2008). In terms of limitations on SRM performance, there was no statistically significant difference in SRM between BTE and CIC hearing aid styles. In this study, hearing aid style was not a major determinant of SRM performance although previous studies showed that the microphone position of BTE aids does convey a disadvantage in some listening conditions (Festen and Plomp, 1986).

Partial correlations between SRM and mean hearing level across the ears, and cognitive variables (working memory and reaction time) were examined, controlling for effects of age. SRM was strongly correlated across all listening conditions, suggesting that SRM under aided and linear-gain listening conditions is determined by similar factors. Reaction time and working memory correlated with each other, though neither was related to SRM. The primary determinant of SRM appeared to be audiometric threshold, with moderate to strong correlations with SRM (see also Ahlstrom *et al.*, 2009). Two conclusions follow from this result. First, although hearing aids can boost SRM by restoring audibility of targets, SRM tends to decrease as hearing worsens, despite aiding. The interpretation for this is that although aids may be able to adequately restore audibility, poorer audiometric thresholds

are associated with poorer spectral and temporal resolution, and it is these factors that may limit SRM performance even when audibility is restored (Peissig and Kollmeier, 1997). Second, as hearing loss increases, the relative benefits of bilateral over unilateral aids also reduces because the amount of SRM for all listening conditions gets smaller (Festen and Plomp, 1986). A large proportion of variance in SRM was not accounted for, however. This may be due to measurement error, or by acoustic or cognitive variables that were not measured in this study (for one such potential cognitive contribution to SRM performance, see Neher *et al.* 2011). If such acoustic or cognitive variables could be identified, they might provide other avenues for improving SRM in hearing impaired listeners. Measurement error may also be addressed by establishing the reliability of measures. Older people tend to have more variable performance on various psychometric measures (MacDonald *et al.*, 2009), so estimates of test-retest reliability based on young listener's performance may be overly optimistic.

## **V. Conclusions**

At group level there was no evidence of any specific T1-T2 improvement in SRM in 'trained' aided listening conditions consistent with acclimatization in new hearing aid users.

Nevertheless, acclimatization effects may be difficult to detect at a group level because of large test-retest variability. Greater T1-T2 improvement in aided listening conditions was associated with greater cognitive capacity (indexed by faster speed-of-processing) and younger age. The amount of hearing aid use was not associated with this improvement. The SRM acclimatization to hearing aids may be greater for younger and more cognitively able people. Bilateral aids facilitated better SRM performance than unilateral aids by around 1.4 dB on average, which is consistent with better preservation by the former of the inter-aural

cues that enable the improvement of speech reception due to spatial separation of target speech and interfering backgrounds. The degree of hearing loss was the primary determinant of SRM for both linear-gain and aided conditions, which suggest that factors associated with elevated thresholds, rather than distortions of inter-aural cues caused by the hearing aids, determine the performance of hearing-aid wearers.

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### **Endnotes**

1. The reason for the mixture of BTE and CIC devices was that CIC devices became available to participants shortly after the commencement of this study. It was found that offering CIC aids as an option increased the participation rate, which is the reason for the greater number of CIC users over BTE users. A comparison of acclimatization outcomes for CIC versus BTE users is included in the results.
2. It was felt that permanently disabling the directional microphone for BTE users would adversely impact on aided listening in the participant's daily life during the 12 week study period. Therefore the procedure used by Marrone et al (2008) of disabling the directional microphone only for SRM testing was adopted.

3. Power calculations using the same assumptions as reported earlier (see the participants section) indicated that a sample size of  $n=34$  would be required to achieve a power of 80% for this comparison.
4. A sample size of  $n=34$  would be required to detect a 2 dB difference in conditions with 80% statistical power, assuming a standard deviation of 4 dB, paired t-test with an alpha level of 0.05.

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Table I. Predictors of acclimatization: Correlations between change in SRM between T1 and T2 and age, cognitive factors (working memory and reaction time), audiometric threshold (PTA) and average daily hearing aid use.

	Average daily hearing aid use	Age	PTA	Working memory	Log reaction time	Change in Linear-gain SRM	Change in Aided SRM
Average daily hearing aid use	-						
Age	-0.07	-					
PTA	-0.01	-0.20	-				
Working memory	-0.08	0.25	-0.34	-			
Log reaction time	-0.12	0.47**	0.16	-0.21	-		
Change in Linear-gain SRM	0.00	-0.25	-0.26	0.05	0.06	-	
Change in Aided SRM	-0.08	-0.41*	0.12	0.07	-0.35*	0.29	-

\*\*  $p < 0.01$ , \*  $p < 0.05$



Table II. Predictors of SRM: Partial correlations between SRM, Cognitive factors (working memory and reaction time) and audiometric threshold (PTA), controlling for Age

	PTA	Working Memory	Log Reaction Time	SRM Linear-gain	SRM Unilaterally aided	SRM Bilaterally aided
PTA	-					
Working Memory	-0.30	-				
Log Reaction Time	-0.05	-0.37*	-			
SRM Linear-gain	-0.35*	0.09	-0.15	-		
SRM Unilaterally aided	-0.73**	0.32	-0.06	0.42**	-	
SRM Bilaterally aided	-0.42**	0.14	-0.12	0.46**	0.66**	-

\* $p < 0.05$ , \*\* $p < 0.01$

(Collected figure captions)

FIG 1. Mean audiometric thresholds ( in dB hearing level) for new-unilateral, new-bilateral and experienced-user groups. Error bars show +/- one standard deviation.

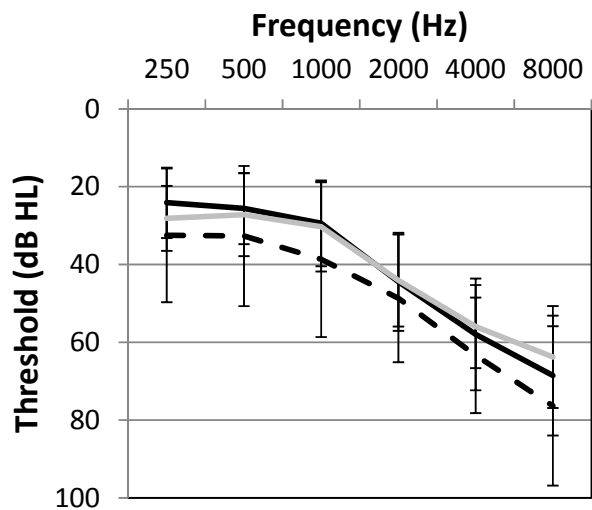
FIG 2. Mean NAL-NL1 real ear insertion gain and targets (in dB) for new and experienced groups. Error bars show +/- one standard deviation.

FIG 3. Mean target-to-masker ratios (T/M) and spatial release from masking (SRM) for identification threshold (in dB) at co-located ( $0^{\circ}$ ) and spatially separated ( $\pm 90^{\circ}$ ) conditions for linear-gain, unilaterally aided and bilaterally aided listening conditions and for new-unilateral, new-bilateral and experienced hearing aid users at T1 and T2. Error bars show +/- one standard deviation. Target to masker ratios (T/M) are the threshold signal to noise ratio required for 50% recognition of the target. SRM is calculated as the threshold target to masker ratio for the co-located listening condition minus the spatially separated condition, so that larger SRM values represent greater benefit in speech recognition from spatial separation. \* indicates that the difference is statistically significant at  $p < 0.05$ .

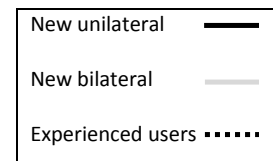
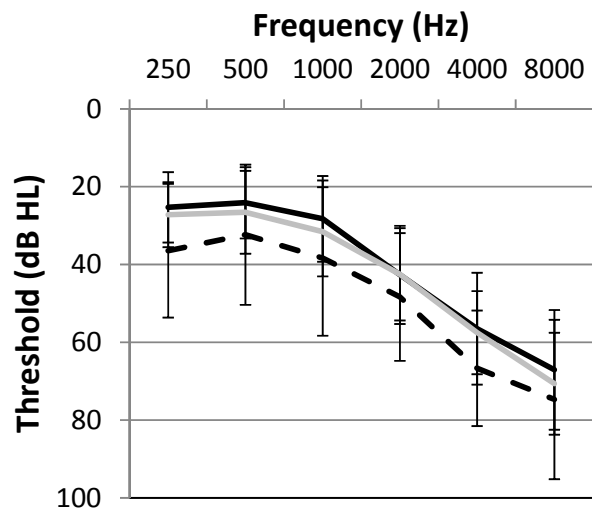
FIG 4. Scatter plots showing change in SRM and age and reaction time for new hearing aid users (unilateral and bilateral groups). 'Change in Aided SRM' refers to the difference in performance (T1-T2) for the familiar aided condition for each new-user group (i.e. the fitted ear condition for the new-unilateral group, and the bilateral aided listening condition for the

new-bilateral group). The dotted line represents the zero point on the x axis. For the two plots on the right of the figure, the sloping solid back line is the regression line.

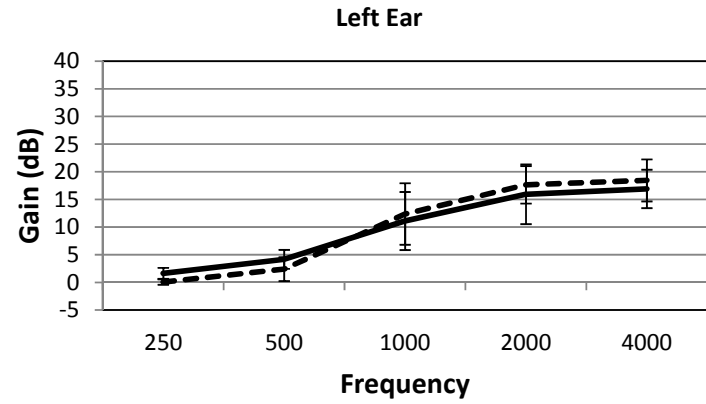
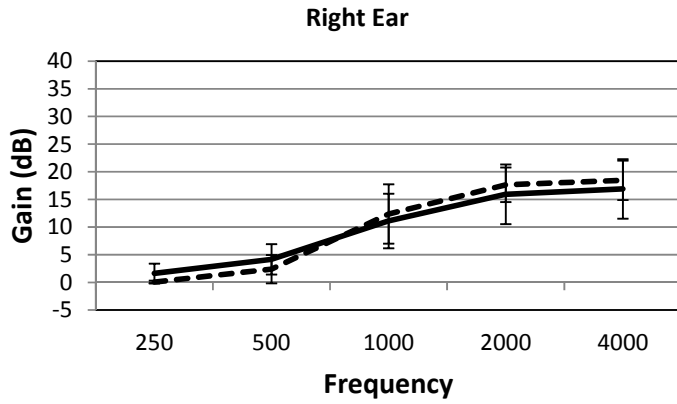
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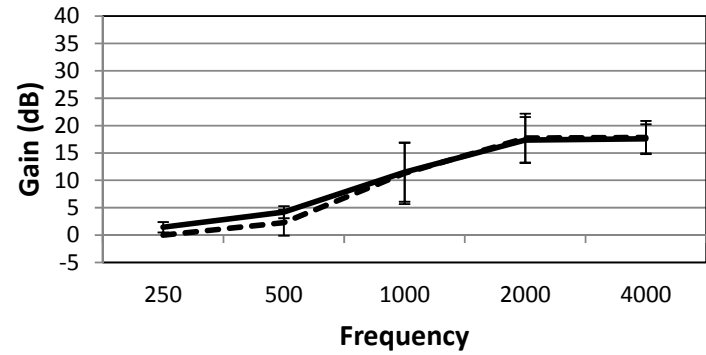
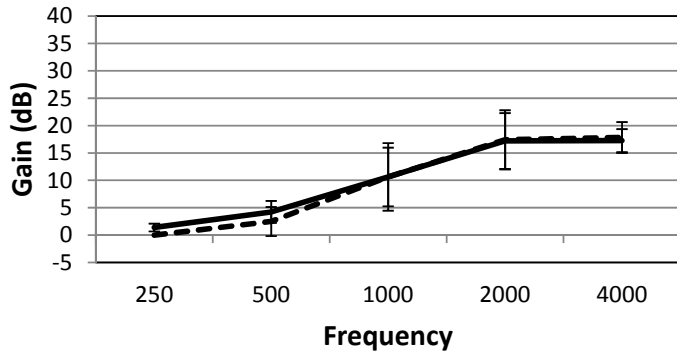
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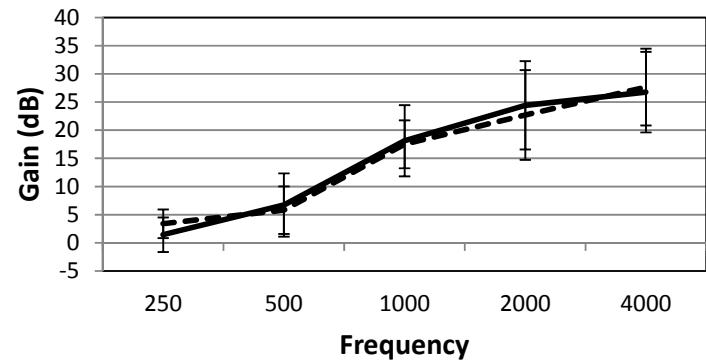
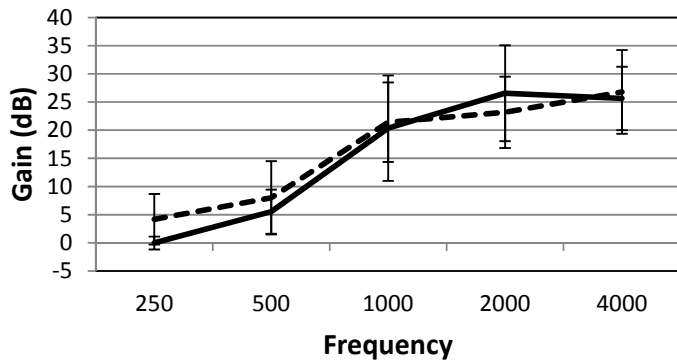
New  
Unilateral



New  
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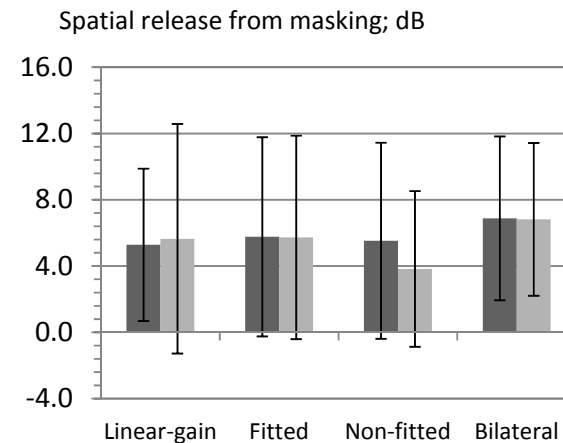
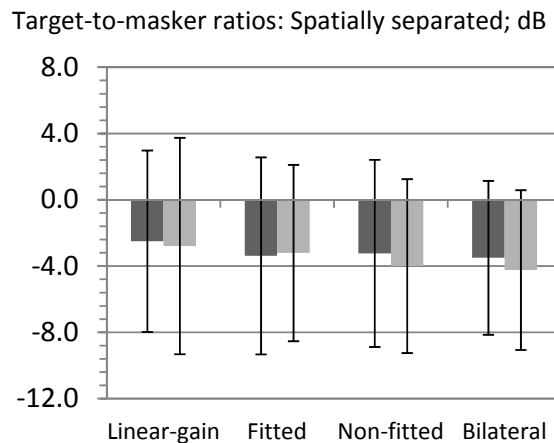
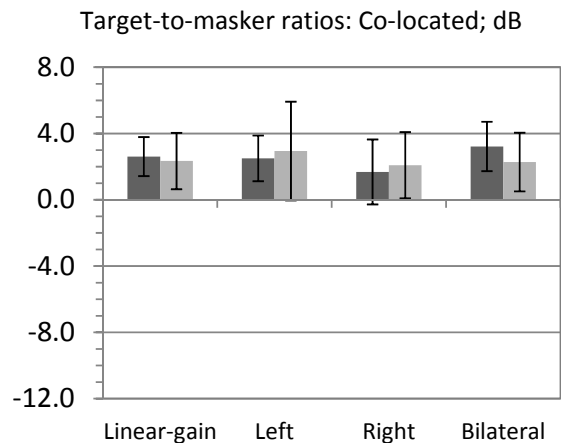
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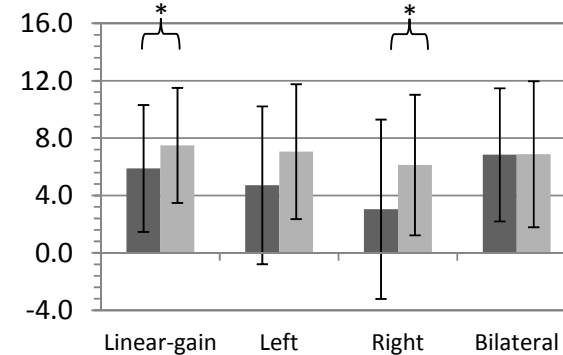
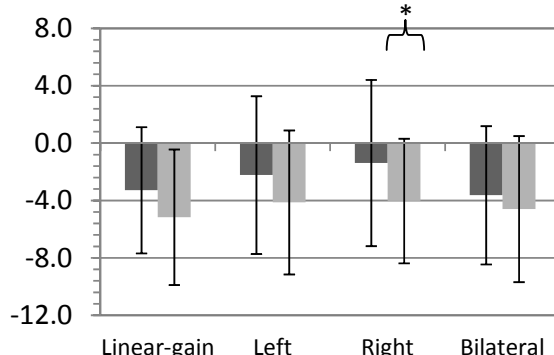
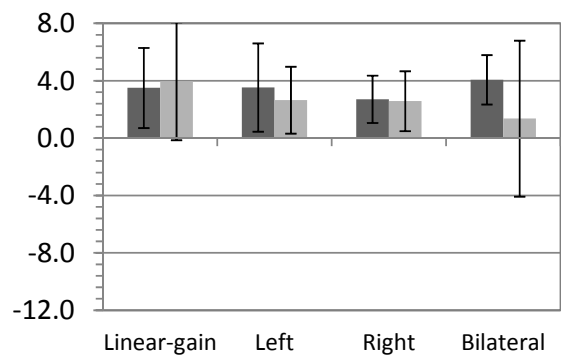
User Gain ———  
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New unilateral



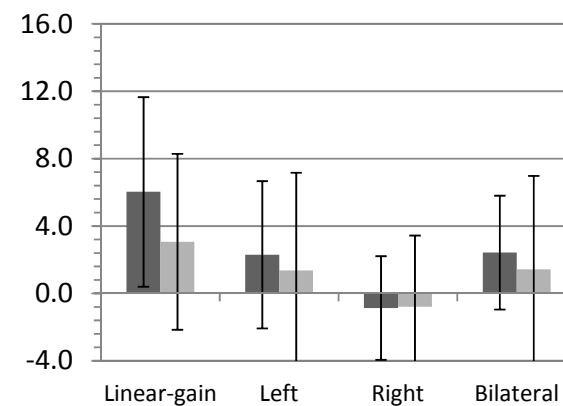
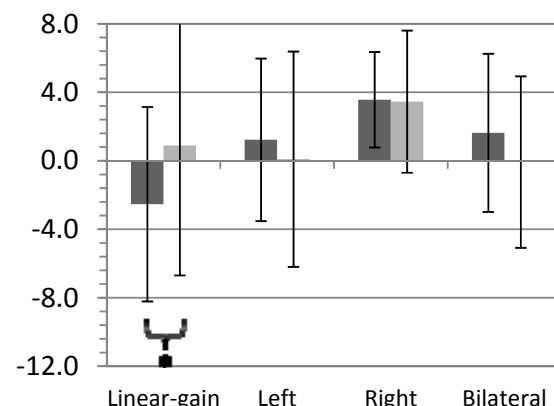
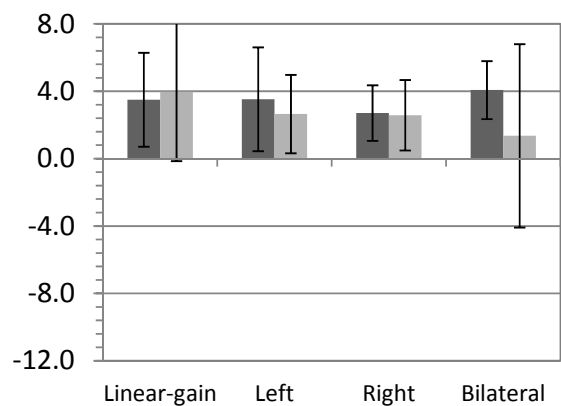
New Bilateral



Experienced

T1

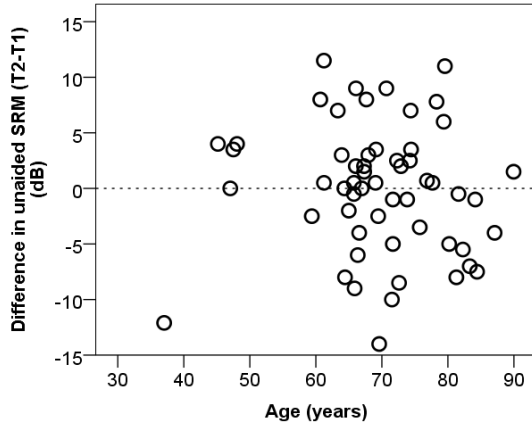
T2







Linear-gain SRM



Aided SRM

