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Predictors of aided speech recognition, with and without frequency compression, in older adults

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Abbreviations

TMT-A/B = Trail Making Test A/B

RST = Reading Span Test

FC = Frequency Compression

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Objective: The aim was to investigate whether cognitive and/or audiological measures predict aided speech recognition, both with and without frequency compression (FC).

Design: Participants wore hearing aids, with and without FC for a total of 12 weeks (six weeks in each signal processing condition, ABA design). Performance on a sentence-in-noise recognition test was assessed at the end of each six week period. Audiological (severity of high frequency hearing loss, presence of dead regions) and cognitive measures (reading span and trail making test scores) were obtained and assessed as predictors of sentence-in-noise recognition with and without FC enabled.

Study sample: Twelve experienced hearing aid users (aged 65-84 years old) with moderate-to-severe high-frequency hearing loss took part in the study.

Results: The results suggest that both auditory and cognitive factors can be predictive of sentence-in-noise recognition with conventional amplification. However, only auditory factors were significantly correlated with the degree of benefit obtained from FC.

Conclusions: The strongest predictor of aided speech recognition, both with and without FC, was high frequency hearing loss. Cognitive performance was also a predictor of benefit from conventional amplification, but not of additional benefit from the use of FC.

Individual differences play a significant role in determining the success of a hearing aid fitting, be that in terms of speech perception scores, hearing aid usage or satisfaction (see for example, Humes, 2007).

Determining the specific nature of the individual differences that relate to, and may be predictive of, hearing aid outcome has been the subject of much research. The aim of the present study was to investigate whether cognitive and audiological factors can be used to predict benefit from frequency compression devices in experienced adult hearing aid users.

The contribution of audiological factors as a predictor of speech perception outcomes following amplification is normally limited to a discussion of hearing thresholds. However, a number of other variables may also fall within this category. Specifically, duration of deafness (or auditory deprivation), previous hearing aid use, or the presence of cochlear dead regions.

Unsurprisingly, most studies seeking to explain individual differences in aided speech perception have identified differences in hearing thresholds as the main source of variance (see for example, Humes, 2007; Tun and Wingfield, 1999). However, the influence of hearing thresholds on speech perception outcome seems to be affected by the type of speech test administered. Specifically, audiometric thresholds tend to account for more variance in relatively easy tasks (such as identifying words in a quiet background) than for more complex tests, such as sentence-in-noise recognition, (Humes, 2007). This is supported by the finding that predictions of the speech in noise recognition scores of older adults, based on audiometric factors, normally overestimate performance, whilst speech in quiet predictions are, as a rule, much more accurate (Hargus and Gordon-Salant, 1995).

Thus, once a task becomes more demanding, the influence of audibility on performance is diminished and the influence of cognitive factors become more pronounced. This seems reasonable given that in order to perceive any sound, the signal must first be detected by the ear, transferred successfully to the brain and then interpreted using cognitive skills. If the signal is relatively intact upon reaching the brain (and not degraded to begin with), fewer cognitive resources will be needed to decipher the signal. If, however, the

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signal is degraded in some way, be it via a noisy background, an impaired auditory system or a hearing aid processor, more cognitive resources will be required to make sense of the degraded signal.

In order to make use of degraded perceptual cues, one must have the capacity to allocate sufficient cognitive resources to the task at hand. This process is likely to involve a number of specific cognitive abilities, but seems to be most accurately indexed using complex working memory span tests. Working memory (Baddeley and Hitch, 1974) is a limited capacity system used to temporarily store and manipulate incoming information and, to an extent, to allocate attentional resources accordingly. In a review of studies linking cognition and speech in noise perception, measures of working memory span, such as the reading span test (Daneman and Carpenter, 1980; Rönnberg et al, 1989), were found to be the most reliable predictor of test performance once the influence of audibility had been accounted for (Akeroyd, 2008). Lunner (2003), for example, found that, after controlling for the effects of audibility and age, reading span test score was correlated with both aided and unaided recognition of speech in noise.

Whilst it is generally agreed that cognitive factors are more predictive of speech perception performance when the stimulus is degraded in some way, there is some evidence to suggest that the degree to which working memory span predicts speech recognition may be dependent on the degree to which the stimuli differs from phonological representations stored in the long term memory, rather than simply the degradation itself. Rönnberg and colleagues (2003, 2008) proposed a working memory model for ease of language understanding. The model suggests that as long as listening conditions are favourable, speech stimuli are implicitly processed and compared to representations stored in the long term memory. If listening conditions are compromised in some way, be it via noise, hearing loss or hearing aid processing, a mismatch may occur between the stimuli being presented and the representation stored in the long term memory. The model suggests that when such a mismatch occurs, explicit storage and processing resources are required and listening becomes more cognitively demanding (Rudner and Rönnberg, 2008).

Rudner et al (2008) found that in a sample of 102 experienced hearing aid users, working memory span scores did indeed show greater correlation with aided speech in noise perception scores when they were tested with novel compression release times (mismatch condition) compared to when they were tested using the compression release time to which they were accustomed (match condition). These results are of particular interest as they demonstrate that the characteristics of the signal processing strategy used in hearing aids can affect the relationship between cognition and speech in noise perception. Lunner (2003) also suggested that it is important to note that the hearing aid processing may in itself be cognitively demanding. This is in agreement with the results reported by Gatehouse et al (2006) and Cox and Xu (2010) who showed that listeners with greater cognitive skills were more likely to benefit from fast acting compression than those with poorer cognitive performance. The implication from the mismatch theory is that the more the hearing aid processing causes the signal to differ from the representation stored in the long term memory, the greater the predictive role of cognition will be.

One method of signal processing that may increase the likelihood of mismatches occurring relative to conventional amplification is non-linear frequency compression (FC). FC is a method of processing an input signal such that information above a specified cut-off point is amplified and compressed in frequency, whilst low and mid frequency information, below the cut-off point, is simply amplified. This method of processing is employed in a range of hearing aids manufactured by Phonak AG (Switzerland).

The results of previous clinical studies of FC hearing aids have shown mixed results with some listeners appearing to receive significant speech perception benefit from FC, whilst others obtain no additional benefit above that provided by conventional amplification (see for example: Simpson et al, 2005, 2006; Glista et al, 2009; Wolfe et al, 2010, 2011; Ellis and Munro, under review).

Previous studies investigating FC in listeners with a hearing loss have provided some evidence that age (with children obtaining more benefit than adults) and severity (or configuration) of hearing loss may be predictive of performance with FC (with listeners with poorer thresholds at high frequencies, but not those with sloping severe hearing loss, obtaining the most benefit) on some speech perception measures.

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However, cognitive factors have not yet been investigated as predictors of benefit from FC in listeners with a hearing loss. Arehart et al (2013) report finding a relationship between performance in the reading span test and sentence in noise recognition with different FC settings in listeners with and without HL. It is important to note, however, that in this study FC was used merely as a method to distort the signal and not applied in the same way as in clinical practice. Furthermore, the FC algorithm studied is different to that used in the Phonak range of hearing aids and is not available commercially in any hearing devices. As such, one should be cautious when extrapolating these findings to the speech perception outcomes of listeners with individually determined FC parameters, prescribed in order to reduce the distortion caused by a hearing loss rather than to introduce additional distortion.

The extent to which working memory capacity and executive function predicted sentence in noise performance in listeners with normal hearing, when the stimuli were processed with and without FC, was investigated by Ellis and Munro (2013). The results showed that cognitive scores were predictive of recognition of speech in noise when it had not been processed using FC. The fact that no evidence of a relation between cognition and the perception of frequency compressed speech was observed may have been influenced by the fact that the listeners in this study had no experience of FC. Thus, it is of interest to determine whether, in a sample of experienced hearing aid users, cognitive factors can be used to predict the recognition of frequency compressed sentences in noise after a period of acclimatisation.

Therefore, the aim of the current study was to investigate the extent to which audiometric and cognitive factors predict both speech perception scores with conventional amplification and additional benefit from FC in experienced adult hearing aid users.

METHOD

Participants

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Twelve adults (aged between 65 and 84 years old, median = 75.5 years old) with symmetrical bilateral moderate-to-severe high-frequency sensorineural hearing loss and >1 year hearing aid experience took part in the study. Ethical approval was granted by Greater Manchester West Research Ethics Committee on behalf of the NHS (Approval code: 10/H1014/44).

Table 1 here

Further details of each participants hearing loss and relevant history are provided in Table 1 and described in greater detail in Ellis and Munro (under review). Hearing thresholds were measured using pure tone audiometry and the presence of dead regions was measured using the TEN test (Moore et al, 2000; 2004). Frequencies between 250 and 8000 Hz were assessed using a TEN noise level of at least +10 dB SL.

Hearing Aid Fitting and Verification

Participants were provided with Phonak Naida V SP hearing aids for use in the study. The hearing aids were fitted bilaterally and matched to NAL-NL2 prescription targets (Keidser et al, 2011) with frequency compression disabled. The hearing aid fitting and verification procedures used in this study are described in depth in Ellis and Munro (under review).

Study Design

The results reported in the current paper are a subset of results obtained in a longer trial reported by Ellis and Munro (under review). In summary, the trial took approximately 18 weeks to complete and was split into four parts. A single group design was used. Prior to fitting the frequency compression hearing aids, there were 3 sessions comprising of the initial screening tests and familiarisation with the speech tests.

After fitting the hearing aids, an A-B-A design was used. All participants wore the hearing aids with frequency compression disabled first (for a mean duration of 3.63 weeks, $SD = 0.81$), then enabled (for a mean duration of 6.57 weeks, $SD = 0.95$) then disabled again (for a mean duration of 3.95 weeks, $SD = 2.75$). Thus, the participants wore the devices at home for approximately six to seven weeks with each setting. According to Gatehouse (1992), at least four-six weeks are required to begin to acclimatise to a new hearing aid setting. Participants completed a number of speech tests on six occasions with frequency compression enabled and disabled. All tests were conducted in a quiet room, acoustically representative of a normal living room. Only the results of the speech in noise test obtained in the session following six weeks experience of FC use and the mean of the results obtained after 3 and 6 weeks of experience without FC will be discussed in this article. The remaining results are discussed in a paper on benefit from FC and acclimatisation to FC respectively (Ellis and Munro, in press). Participants also completed the Reading Span Test and the Trail Making Tests A and B on two occasions, once at the first testing session and once at the penultimate testing session. The mean of the scores obtained on these two occasions were calculated.

Outcome measures

Sentence-in-Noise recognition

Participants were presented with lists of 10 Institute of Electrical and Electronics Engineers (IEEE) sentences (Rothauser et al, 1969; for example, ‘the last switch cannot be turned off’) spoken by a female talker and presented in a background of 20 talker babble noise (Auditec, St Louis, USA). The sentences were presented via a loudspeaker situated at head height one meter from the listener at zero degrees azimuth. The level at which the sentences were presented was kept constant throughout each list, however, the level of the noise varied from +15 to -12 dB in a fixed order, one sentence at each SNR, similar to the method recommended by Wilson et al (2007). Sentences were presented at 55 dB SPL for

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all participants with the exception of one (participant 008) who was unable to complete the task at this level. For this listener, sentences were presented at 65 dB SPL. Participants were asked to repeat each sentence back to the experimenter and the percentage of keywords (5 per sentence) correctly recognised was calculated. Three sentence lists were administered on each occasion of testing. The same sentences lists were used for all participants but were randomly allocated to different test conditions.

Cognitive measures

Participants completed the Reading Span Test (RST) and the Trail Making Tests (TMT) A and B on two occasions, once at the first testing session and once at the penultimate testing session.

The Reading Span Test (Daneman and Carpenter, 1980; Rönnerberg et al, 1989) consists of a sequence of sentences in blocks of 3-6. Sentences were presented to the participant, word by word, on a computer screen at the rate of one word every 800 ms. Immediately after reading each sentence, the participant must state whether the sentence made sense giving a yes-no response (processing component). At the end of each block, participants were asked to recall either the first or last word of every sentence in that group (storage component). The order in which participants were asked to recall either first or last words of each sentence was randomized. In the first trial, three sentences were presented. In each subsequent trial the number of sentences presented was increased by one, up to six sentences in the final trial. Upon completion of the test, the percentage of words correctly recalled was then calculated. The percentage of errors made in the processing component of the task was also calculated.

The Trail Making Tests A and B (TMT-A/B, Reitan, 1958, 1992) are paper and pencil based tasks thought to index processing speed and executive function. The TMT was included in the study as it has been shown that performance on the TMT may predict the ability of listeners with a hearing loss to perceive speech in a novel accent (Adank and Janse, 2010). As frequency compression alters the spectral

relationship between speech components, perception of speech processed in this way may require similar skills to those needed to perceive speech in a novel accent. The participants' task was to join together a series of points on a sheet of paper in the correct order without allowing their pencil to leave the page. In the TMT-A, the points are labelled from 1-25, the task being to join the points in the correct numerical order. In the TMT-B, the points are labelled 1-12 and A-L and the participants' task was to join the points in the correct alphabetical and numerical order, alternating between the two (for example, 1-A-2-B-3-C and so on). Prior to completing the TMT tests, the participants were given a sample task on which to practice. Performance on the task was assessed by measuring the total time taken to complete each task. If the participant made a mistake, the experimenter pointed out their error and asked the participant to correct it. Errors were penalized only in that they increased the time taken to complete the task. Participants were aware that the time taken to complete the task was the outcome measure of interest.

Analysis

Pearson's correlation coefficient was calculated to investigate the relationship between possible predictors of benefit from frequency compression and scores on the sentence recognition in noise (SIN) test.

Predictors were correlated with both the mean percentage correct SIN score without FC and with the additional benefit obtained from frequency compression after 6 weeks use (mean SIN % correct at FC6 – mean SIN % correct without FC). Potential audiological predictors included mean high frequency pure tone threshold (mean of thresholds at 2, 4, 6 and 8 kHz) in the better ear (HFPTA) and the presence of dead regions (DRs). The influence of HFPTA was partialled out for all subsequent correlations. Partial correlation was achieved using a general linear model in which the variable of interest (in this case, HFPTA) is correlated with variable A, which is then recalculated so as to remove the effects of HFPTA. The recalculated variable A is then correlated with variable B to give the correlation between variables A and B with the effects of HFPTA controlled for. As a result of these analyses, some of the axes in the included figures contain negative numbers, when this would not intuitively seem to make sense.

The presence of DRs was coded as a dichotomous variable (where 0 = no DRs and 1 = one or more DRs in at least one ear), therefore a point biserial correlation analysis was conducted. Possible cognitive predictors included mean percentage correct on the RST, mean percentage error rate on the RST, mean TMT-A score and mean TMT-B score. Despite the multiple correlations, a Bonferroni correction was not applied as it was felt that the increase in the risk of a Type 2 error occurring outweighed the potential benefits of reducing the risk of a Type 1 error (see Cabin and Mitchell, 2000 for a discussion of when to use the Bonferroni correction).

RESULTS

Audiological Predictors

HFPTA

Inspection of the scatterplots shown in the left hand column of Figure 1 indicate a negative correlation between HFPTA and mean SIN scores without FC (upper panel) and a positive correlation with benefit obtained from FC (lower panel). These correlations are both statistically significant, albeit borderline in relation to benefit from FC (No FC: $r = -0.92$, $p < 0.001$; benefit from FC: $r = 0.59$, $p = 0.045$).

Figure 1 here

Presence of DRs

The scatterplots shown in the right hand column of Figure 1 suggest that there is no relationship between the presence of DRs and performance in the SIN test either with (lower panel) or without (upper panel) FC. The analysis confirmed that these correlations are not statistically significant (No FC: $r = -0.03$, $p = 0.925$; benefit from FC: $r = 0.13$, $p = 0.705$).

Cognitive Predictors

RST: % Correct Recall

The mean RST % correct was 29 (SD = 11.09). An inspection of the scatterplots presented in the left hand column of Figure 2 suggest a trend for a positive relationship between RST % correct scores and performance on the SIN test without FC (upper panel). However, there is no evidence of a relationship between RST % correct recall and benefit obtained from FC (lower panel). The results of the statistical analyses show that neither of these correlations reaches statistical significance (No FC: $r = 0.53$, $p = 0.094$; benefit from FC: $r = -0.17$, $p = 0.625$).

Figure 2 here

RST: % Processing Errors

The mean percentage of processing errors in the RST was 6.56 (SD = 6.53). The scatterplots displayed in the right hand column of Figure 2 indicate a negative correlation between RST processing error rate and SIN scores without FC (upper panel) and a positive correlation with SIN scores with FC (lower panel). The results of the statistical analyses indicate that only the correlation between RST error rate and SIN without FC is borderline statistically significant (No FC: $r = -0.60$, $p = 0.050$; benefit from FC: $r = 0.34$, $p = 0.306$).

TMT-A

The mean time taken to complete the TMT-A was 42.92 seconds ($SD = 30.86$). The scatterplots shown in the left hand column of Figure 3 indicate a negative relationship between TMT-A scores and performance in the SIN test without FC. No clear evidence of a relationship between TMT-A score and benefit obtained from FC is apparent in the scatterplot presented in the lower panel of the left hand column of Figure 3. The results of the statistical analyses confirm that only the correlation between TMT-A scores and performance on the SIN test without FC is statistically significant (No FC: $r = -0.69$, $p = 0.018$; benefit from FC: $r = 0.28$, $p = 0.413$).

Figure 3 here

TMT-B

The mean time taken to complete the TMT-B was 95.04 seconds ($SD = 42.56$). The scatterplots displayed in the right hand column of Figure 3 indicate a negative relationship between TMT-B scores and performance in the SIN test without FC (upper panel) with no clear evidence of a relationship between TMT-B scores and benefit obtained from FC (lower panel). The results of the statistical analysis indicate that only the correlation between TMT-B scores and performance on the SIN test without FC is statistically significant (No FC: $r = -0.67$, $p = 0.026$; benefit from FC: $R = 0.06$, $P = 0.851$).

DISCUSSION

The results of the study indicate that, based on the factors investigated, both HFPTA and cognitive function can be used to predict speech recognition outcomes from conventionally amplified speech. However, cognitive performance did not significantly predict additional benefit from FC. This pattern of results is similar to those observed in a study investigating the role of cognition as a predictor of frequency compressed speech recognition in listeners with normal hearing (Ellis and Munro, 2013).

Whilst HFPTA did predict additional benefit from FC, this finding should be considered cautiously given the heterogeneous nature of the sample group.

The observation that high frequency pure tone average loss is predictive of benefit from frequency compression is consistent with results reported by Glista et al (2009). However, it should be noted that in the present study, this result is likely to have been disproportionately influenced by one particular case (evidenced by a Cook's distance value of 1.49, above the cutoff of 1 recommended by Cook and Weisberg, 1982), the participant with the poorest hearing thresholds. This is not to suggest that the results are invalid, only that they should be interpreted cautiously. The findings of both the present study and that conducted by Glista et al (2009) indicate that listeners with greater high frequency losses obtain more benefit from frequency compression than those with less severe high frequency losses. This suggests that benefit from frequency compression is related to the increased audibility of high frequency sounds resulting from this signal processing method.

Once the effect of high frequency hearing loss was partialled out, the presence of dead regions did not predict sentence-in-noise recognition with or without FC enabled. This is in agreement with results reported by Dillon et al (2011), who found that once the effect of hearing loss had been accounted for, dead regions had little effect on the intelligibility of conventionally amplified speech. However, the analysis in the present study was based simply on whether there was evidence of at least one dead region or not. The edge frequency and width of the dead regions was not taken into account. It is perfectly plausible that these factors may need to be considered when selecting the frequency compression cut-off point. Research has suggested that providing amplification at frequencies over 70% above the edge frequency of a dead region may be of limited benefit to listeners (Vickers et al, 2001). It may therefore be the case that compressing high frequency information into this region is also of limited benefit to the listener.

The results indicate that, once the effect of high frequency hearing loss has been partialled out, cognitive performance can be used to predict sentence-in-noise recognition without frequency compression.

Specifically, results in the TMT-A and B tests, along with the percentage of processing errors made in the RST were related to performance in the speech in noise test. Listeners who obtained better scores in the cognitive tests also tended to achieve higher scores in the sentence recognition task. This finding is consistent with the results of previous studies of sentence recognition scores (see Akeroyd, 2008 for a review). However, the percentage recalled correct obtained in the RST, a measure that has often been shown to correlate with aided speech perception scores (see for example, Lunner, 2003), was not predictive of either performance without frequency compression or additional benefit obtained from it. It should be noted that a positive trend between percentage correct on the RST and sentence recognition without frequency compression is evident, however, this relationship did not reach statistical significance.

The percentage correct score on the reading span test is normally seen as a reflection of working memory span whilst the TMT-A and B are generally seen as indices of executive function and task switching abilities. One may also consider performance in the RST, particularly in respect to error rate, to be an index of executive function (see for example, Engle, 2002). Therefore the results of the current study provide some evidence that it may not be working memory span, per se, but rather executive functioning, that is predictive of speech in noise recognition. This seems logical, given that the ability to efficiently perceive speech in noise depends on the capacity to focus attention on the useful parts of the signal, and away from the competing noise, an ability governed by executive function. That the TMT-A and B were shown here to be predictive of aided speech in noise recognition (albeit without frequency compression) may be of clinical interest. These tests require no special equipment and take only minutes to administer thus making them a practical option to administer in a clinical, as well as a research, setting. However, additional research is needed to further investigate the relationship between executive function and speech perception.

The fact that none of the cognitive measures correlated with additional benefit derived from frequency compression on speech recognition scores may be considered in light of the working memory model of ease of language understanding proposed by Rönnerberg and colleagues (2003, 2008, 2013; Rudner and Rönnerberg, 2008). According to the model, cognitive resources are taxed when speech stimuli differ from representations stored in the long term memory. It may be that as changes introduced by frequency compression are concentrated only at the high frequencies, the differences between sentences that have been compressed in frequency and those that have not are not large enough to require additional cognitive resources. Furthermore, it is also possible that frequency compression actually makes speech more similar to the representations stored in the long term memory than conventional amplification, depending on the duration and severity of hearing loss (for example, in cases where frequency compression makes the otherwise inaudible high frequency parts of a phoneme audible with a minimal amount of spectral distortion).

Whilst the sample used in this study was small, there was sufficient power to detect that high frequency PTA, TMT-A score, TMT-B score and RST % errors significantly predicted speech recognition without FC (all except the RST % error retaining their significance even after Bonferroni correction). We suggest that this shows the study has sufficient power to detect these effects, and, that the fact that the cognitive predictors were not associated with benefit from FC is a genuine result, not one arising from a lack of power. In order to investigate whether correlations between each of the cognitive tests and performance without FC were significantly different to the correlations with the degree of additional benefit obtained from the use of FC, we conducted a series of Steiger's Z tests. The results indicate that the TMT-B test may be particularly sensitive to predicting outcomes without FC yet not the degree of additional benefit obtained from the use of FC (Steiger's $Z = -2.27$, $p < .05$).

Conclusions

The results of the study indicate that severity of high frequency hearing loss can be used to predict sentence in noise recognition with conventional amplification and, to some extent, the degree of additional benefit conferred by the use of frequency compression. However, only benefit from conventional amplification could be predicted from cognitive performance. The finding that benefit from FC is not predicted by performance on cognitive tests used in this study suggests that cognitive ability, at least in terms of the skills indexed by the tests administered in this study, does not need to be considered when assessing the potential candidacy for FC. The clinical implication of this finding is that FC may provide additional benefit to that conferred by conventional amplification, even to less cognitively able patients. The findings also suggest that tests of executive function may be useful in a clinical setting with regard to their value in predicting speech perception outcomes without frequency compression.

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Table 1. Characteristics of the participants' hearing loss, previous hearing aid use and the non-linear frequency compression settings used in the trial.

Table 1

Participant	Age at start of trial (years)	Duration of hearing loss (years)	Duration of previous HA use* (years)	Ear	NLFC settings applied: cut-off freq. (CR) in kHz**	NLFC settings prescribed: cut-off freq. (CR) in kHz**	Dead regions (kHz)***	Hearing threshold (dB HL) at specified frequencies (kHz)								
								0.25	0.5	1	1.5	2	3	4	6	8
001	69	10	10 (L)	Right	3.7 (2.6.1)	4.5 (2.8.1)	None	5	0	20	40	45	55	50	50	70
001				Left			None	0	0	35	65	70	70	70	70	60
002	80	20	20 (B)	Right	2 (1.8.1)	3.3 (2.1.1)	3 & 4	25	15	20	30	65	90	90	85	80
002				Left			3 & 4	35	30	35	50	60	80	85	90	75
003	80	10	7 (B)	Right	3.3 (2.4.1)	2.8 (2.3.1)	None	20	25	35	45	55	65	80	85	80
003				Left			4	25	25	30	35	40	55	60	70	75
004	66	10	4 (R)	Right	3.1 (2.4.1)	4.4 (2.7.1)	None	10	30	45	65	60	60	65	65	65
004				Left			None	15	20	30	45	45	55	60	80	65
005	77	5	3 (L)	Right	3.1 (2.4.1)	4.4 (2.7.1)	None	20	5	20	35	40	45	45	75	70
005				Left			None	20	15	35	45	55	60	60	95	85
006	74	8	4 (R)	Right	3 (2.3.1)	4.3 (2.7.1)	None	50	60	60	55	55	55	55	75	65
006				Left			3	50	55	60	60	60	55	40	85	75
007	73	5	1 (L)	Right	3.1 (2.5.1)	4.5 (2.7.1)	None	35	45	45	45	50	60	60	55	60
007				Left			None	30	50	55	50	45	65	60	90	80
008	84	9	3 (B)	Right	2 (1.7.1)	2.7 (1.8.1)	3 & 4	30	40	60	60	55	80	95	105	110
008				Left			3 & 4	35	30	50	70	75	70	95	115	105
009	65	8	4 (R)	Right	2.8 (2.4.1)	3.7 (2.3.1)	None	25	35	50	55	60	60	65	85	85
009				Left			None	15	35	45	55	55	60	55	90	70
010	79	10	8 (B)	Right	2.6 (2.1.1)	4.1 (2.5.1)	None	40	40	45	55	45	65	75	80	90
010				Left			None	30	30	40	45	50	55	60	75	85
011	75	5	5 (L)	Right	3.1 (2.5.1)	4.5 (2.8.1)	None	20	20	30	30	25	35	50	55	80
011				Left			None	30	30	30	30	25	45	35	40	85
012	65	6	3 (L)	Right	2.4 (2.0.1)	3.4 (2.1.1)	1.5, 2.0, 3.0, 4	15	10	25	70	75	70	80	85	75
012				Left			2 (0.5), 4	10	10	10	70	80	85	90	90	75
Mean	71.9	8.8	7.1	n/a	n/a	n/a	n/a	24.8	27.3	37.5	50.7	54.4	61.9	65.8	80.6	77.7

* (L) = left, (R) = right, (B) = bilateral ** CR = compression ratio i = inconclusive

LIST OF FIGURES

Figure 1. Correlations between High Frequency Pure Tone Average (HFPTA, 2,4,6 and 8 kHz) in the better ear and mean percentage correct in the sentence-in-noise test without frequency compression (top left panel) and with benefit obtained from frequency compression (bottom left panel). Partial correlations (with HFPTA controlled for) between the presence of dead regions and the mean percentage correct in the sentence-in-noise test without frequency compression (top right panel) and with benefit obtained from frequency compression (bottom right panel).

Figure 2. Partial correlations (with HFPTA controlled for) between the mean percentage correct obtained on the RST and the mean percentage correct in the sentence-in-noise test without frequency compression (top left panel) and with benefit obtained from frequency compression (bottom left panel). Partial correlations (with HFPTA controlled for) between the mean percentage of errors obtained on the RST with the mean percentage correct recall in the sentence-in-noise test without frequency compression (top right panel) and with benefit obtained from frequency compression (bottom right panel).

Figure 3. Partial correlations (with HFPTA controlled for) between the mean TMT-A scores and the mean percentage correct in the sentence-in-noise test without frequency compression (top left panel) and with benefit obtained from frequency compression (bottom left panel). Partial correlations (with HFPTA controlled for) between the mean TMT-B scores with the mean percentage correct in the sentence-in-noise test without frequency compression (top right panel) and with benefit obtained from frequency compression (bottom right panel).

Ellis & Munro, Predictors of aided speech recognition
Figure 1

Ellis & Munro, Predictors of aided speech recognition
Figure 2

Ellis & Munro, Predictors of aided speech recognition
Figure 3