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| **Complete List of Authors:** | Neher, Tobias; Eriksholm Research Centre  
Behrens, Thomas; Eriksholm Research Centre  
Carlile, Simon; University of Sydney, Auditory Neuroscience Laboratory  
Jin, Craig; University of Sydney, Computing and Audio Research Laboratory  
Kragelund, Louise; Eriksholm Research Centre  
Specht Petersen, Anne; Eriksholm Research Centre  
van Schaik, André; University of Sydney, Computing and Audio Research Laboratory |
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Benefit from Spatial Separation of Multiple Talkers in Bilateral Hearing-Aid Users: Effects of Hearing Loss, Age and Cognition

Tobias Neher\textsuperscript{1}, Thomas Behrens\textsuperscript{1}, Simon Carlile\textsuperscript{2}, Craig Jin\textsuperscript{3}, Louise Kragelund\textsuperscript{1}, Anne Specht Petersen\textsuperscript{1} and André van Schaik\textsuperscript{3}

\textsuperscript{1} Eriksholm Research Centre, Oticon A/S, Kongevejen 243, 3070 Snekkersten, Denmark
\textsuperscript{2} Auditory Neuroscience Laboratory, School of Medical Sciences, University of Sydney, NSW, Australia
\textsuperscript{3} Computing and Audio Research Laboratory, School of Electrical and Information Engineering, University of Sydney, NSW, Australia

KEY WORDS
Spatial hearing, spatial release from masking, speech-on-speech masking, hearing aids, hearing loss, age, cognition, attention, working memory

CORRESPONDING AUTHOR
Tobias Neher, Eriksholm Research Centre, Kongevejen 243, 3070 Snekkersten, Denmark
ton@oticon.dk
LIST OF ACRONYMS AND ABBREVIATIONS

4FA-HL: Four-frequency average hearing level measured across both ears and across 0.5, 1, 2 and 4 kHz

4FA-HL\textsubscript{low}: Four-frequency average hearing level measured across both ears and across 0.125, 0.25, 0.5 and 0.75 kHz

4FA-HL\textsubscript{high}: Four-frequency average hearing level measured across both ears and across 2, 3, 4 and 6 kHz

4FA-HL\textsubscript{high, aided}: Four-frequency average hearing level measured across both ears and across 2, 3, 4 and 6 kHz under aided conditions

CIC: Completely-in-the-canal

F-B: Front-back

ILD: Interaural level difference

ITD: Interaural time difference

L-R: Left-right

SNR: Signal-to-noise ratio

SRM: Spatial release from masking

SRT: Speech reception threshold

TEA: Test of everyday attention

TMR: Target-to-masker ratio
ABSTRACT

To study the spatial hearing abilities of bilateral hearing-aid users in multi-talker situations, 20 subjects received fittings configured to preserve acoustic cues salient for spatial hearing. Following acclimatization, speech reception thresholds (SRTs) were measured for three competing talkers that were either co-located or spatially separated along the front-back or left-right dimension. In addition, the subjects’ working memory and attentional abilities were measured. Left-right SRTs varied over more than 14 dB, while front-back SRTs varied over more than 8 dB. Furthermore, significant correlations were observed between left-right SRTs, age and low-frequency hearing loss, and also between front-back SRTs, age and high-frequency aided thresholds. Concerning cognitive effects, left-right performance was most strongly related to attentional abilities, while front-back performance showed a relation to working memory abilities. Altogether, these results suggest that, due to raised hearing thresholds and aging, hearing-aid users have reduced access to interaural and monaural spatial cues as well as a diminished ability to “enhance” a target signal by means of top-down processing. These deficits, in turn, lead to impaired functioning in complex listening environments.
1 INTRODUCTION

It is well established that spatial hearing plays an important role in situations where, apart from 
the sound of interest, other interfering sounds are present, for example at cocktail parties (e.g. 
Bronkhorst, 2000; Ebata, 2003; Yost, 1997). This is due to the fact that when competing sound 
sources are spatially separated, certain acoustical and perceptual mechanisms come into play that 
can lead to large speech intelligibility improvements (e.g. Freyman et al, 1999; Zurek, 1993). In 
order to be able to take advantage of these mechanisms, however, listeners have to have access to 
spatially salient acoustical cues. There is a large body of research showing that spatial hearing is 
mediated by three main types of acoustical cues: interaural time differences (ITDs), interaural 
level differences (ILDs) and monaural spectral cues (see Blauert, 1983, for a review). These cues 
differ in terms of the frequencies at which they occur and the spatial information they provide.

ITDs arise as a result of the physical separation of a listener’s ears and provide information about 
the left-right position of a sound source. Even though neural firing tracks the phase of a signal up 
to about 1.5 kHz, ITDs are perceptually most potent below about 0.75 kHz. Like ITDs, ILDs vary 
with a sound source’s position along the left-right dimension. They arise from the sound 
attenuation caused by the listener’s head acoustically shadowing frequencies above ca. 2 kHz, 
thereby leading to contralateral high-frequency attenuation of a lateral sound signal. Monaural 
spectral cues arise from acoustic filtering by the human outer ear, which filters particularly the 
high-frequency components of sounds in a direction-dependent manner. This filtering gives rise 
to characteristic spectral changes above ca. 2 kHz that provide information about a sound 
source’s position along the front-back and up-down dimensions.
While normal-hearing subjects are generally able to exploit these spatial cues, various studies have shown that a sensorineural hearing loss usually leads to impaired spatial hearing abilities. This holds true for sound localization (e.g. Lorenzi et al, 1999; Noble et al, 1994; Noble, Byrne & Ter-Host, 1997; Rakerd et al, 1998), detection of the spatial separation of two sound sources (Noble, Byrne & Ter-Host, 1997), and detection or recognition of a target signal that differs in spatial cues from one or more competing signals (Gelfand et al, 1988; Grose et al, 1994; Helfer & Freyman, 2008; Pichora-Fuller & Schneider, 1991). These performance deficits have been traced back not only to reduced audibility, but also to supra-threshold spectro-temporal processing deficits that can limit access to spatial cues (e.g. Moore, 1998). In addition to such peripheral deficits, cognitive impairments may also be involved, for example reduced working memory capacity or a diminished ability to focus on a target message and suppress interfering information (e.g. Pichora-Fuller & Singh, 2006). These effects tend to accompany aging (e.g. Salthouse, 1982) and could therefore limit an elderly hearing-impaired listener’s performance even more, especially in multi-talker situations with highly similar competing signals (e.g. Tun et al, 2002).

In principle, apart from hearing loss and reduced cognitive function, hearing aids can restrict the availability of salient spatial cues as well, for example because of non-optimal microphone placement, insufficient amplification, or bilaterally independent compression or noise reduction. Indeed, poorer aided than unaided performance has been observed in various sound localization studies (Byrne et al, 1995; 1996; Noble et al, 1998; Van den Bogaert et al, 2006). Nevertheless, as far as the spatial listening abilities of hearing-aid users in more complex environments are concerned, the situation is not as clear. Festen and Plomp (1986) measured the effect of
separating speech and speech-shaped noise along the left-right dimension on the speech reception
thresholds (SRTs) of bilateral hearing-aid users who were tested either with their personal
hearing aids or without them. In the latter case, higher presentation levels were used to
compensate for reduced audibility. Although aided performance was poorer than unaided
performance, the subjects obtained some benefit from left-right separation in both cases,
especially if they had a milder hearing loss. In a similar study, however, a group of hearing-aid
users showed only a very small improvement or even a performance decrement when a speech
and noise signal were separated along the left-right dimension, both with and without unfamiliar
bilateral amplification (Noble, Sinclair & Byrne, 1997). Recently, Marrone et al (2008a) tested
bilateral hearing-aid users on a task that involved left-right separating three concurrent, same-sex
talkers. Measurements were made both with the subjects’ personal hearing aids and without them
at an equivalent sensation level, essentially corresponding to providing uniform amplification. In
each case, the subjects obtained several dB of spatial benefit.

From the above, it is apparent that only a few free-field studies have examined the ability of
hearing-aid users to take advantage of spatial cues. Furthermore, the results from these studies
differ somewhat in terms of the degree of spatial benefit observed, some of these differences
probably being due to the use of the subjects’ own hearing aids (the types and settings of which
were not controlled for) or the use of unfamiliar amplification (thereby preventing
acclimatization). It is also noteworthy that, despite the fact that hearing-aid users find situations
involving multiple speech sources particularly problematic (e.g. Noble & Gatehouse, 2006), only
the study by Marrone et al (2008a) seems to have looked at the performance of hearing-aid users
in a speech-on-speech masking context. Consequently, this study was designed to shed more light on speech recognition by bilateral hearing-aid users in multi-talker listening environments. More precisely, the aim was to quantify performance in conditions with and without spatial separation of three competing, same-sex talkers and to elucidate how benefit from spatial separation varies with hearing loss, age and cognitive function. Since these factors might differentially affect access to different types of spatial cues, both a left-right and a front-back spatial separation condition were included in this study. Finally, rather than comparing aided with unaided performance as done by other investigators, this study took the approach to fit all subjects with, and acclimatize them to, new bilateral hearing aids that were all of the same type and that were all configured to preserve salient spatial cues.

2 METHODS

2.1 Test subjects

Twenty test subjects, eight female and twelve male, aged 28-84 years (mean = 60 years; cf. Figure 6) participated in this study. They all had a gently sloping hearing loss with four-frequency average hearing levels (4FA-HLs), as measured across 0.5, 1, 2 and 4 kHz and across both ears, of 33-56 dB HL (mean = 43 dB HL; cf. Figure 1). The asymmetry in hearing thresholds between the two ears was within 15 dB for all audiometric frequencies and for all subjects. In addition, the average hearing loss across the audiometric frequencies of 0.125, 0.25, 0.5 and 0.75 kHz (4FA-HL\textsubscript{low}; mean = 28 dB HL, range = 11-43 dB HL) as well as 2, 3, 4 and 6 kHz (4FA-HL\textsubscript{high}; mean = 54 dB HL, range = 41-67 dB HL) was calculated across the two ears of each subject (note that these two measures were not correlated; \(r = 0.12\)). In terms of
experience with amplification, all subjects were fitted previously with bilateral hearing aids for at least six months. The subjects’ own hearings aids were either completely-in-the-canal (nine), in-the-canal (six) or behind-the-ear (five) devices. Furthermore, ten subjects were accustomed to a vent size of 1.4 mm or smaller, five subjects were accustomed to a vent size between 2.4 and 4.0 mm, and the other five subjects were accustomed to open fittings. All subjects had normal vision or normal vision with eyeglasses. They were reimbursed for their travel expenses, but otherwise not paid for their participation.

2.2 Hearing aids

At the beginning of the study, all subjects were bilaterally fitted with experimental completely-in-the-canal (CIC) hearing aids using Oticon’s Voice Aligned Compression rationale as a starting point. These hearing aids were equipped with 15 heavily coupled compression channels (corresponding to a maximum of three independent compression channels) and feedback cancellation systems. Furthermore, they had an output bandwidth of ca. 7 kHz and, in order to maintain natural timing relationships, a constant throughput delay of 10 ms. CIC devices were chosen to ensure that the hearing-aid microphones were located as close to the ear-canal entrance as possible, so that the spectral cues that arise from outer-ear filtering would be preserved by the fittings. In addition, an effort was made to improve access to these cues in the 2-7 kHz region, where information salient for front-back discrimination is located (e.g. Carlile & Pralong, 1994; Wightman & Kistler, 1997). To that end, audibility in that frequency region was first verified by measuring free-field aided thresholds in an audiometric booth. Each ear was measured separately by occluding the other ear with an ear muff. The test signal used was one-third octave noise with
a centre frequency of 1, 2, 3, 4 or 6 kHz. For each of these frequencies, a target threshold was
defined based on the one-third octave speech levels corresponding to an overall level of
65 dB SPL specified in (ANSI S3.5, 1997) to ensure that high-frequency speech sounds would
generally be audible.ii Since the ANSI levels are based on long-term spectra and since speech is
generally dominated by vowels and hence lower-frequency energy (e.g. Byrne et al, 1994), it is
possible that the higher-frequency speech levels were somewhat underestimated. For that reason,
an analysis of consonant levels was first carried out. From this, it was concluded that at 4 and
6 kHz typical consonant segments contain, on average, about 10 dB more energy than what is
indicated by the long-term average of speech. Hence, the target thresholds for these frequencies
were adjusted accordingly. If, for a given subject and frequency, the target threshold was not
achieved, the amplification in the subject’s device was increased and another audibility test was
carried out. This procedure was then repeated until the threshold was as close to the target as
possible. Figure 2 displays the one-third octave ANSI levels, the target thresholds that were
defined, and the mean, minimum and maximum aided thresholds that the subjects obtained, all
plotted in dB(A) SPL. As can be seen, the subjects’ aided thresholds were generally within the
targets that were set. The only major exception was at 6 kHz where, as a result of making sure
that all fittings were comfortable, the group average fell slightly short of the target. For each
subject, the aided thresholds corresponding to centre frequencies of 2, 3, 4 and 6 kHz were
averaged, and these averages are referred to as 4FA-HL_{\text{high\_aided}}.

The attack times of the hearing aids’ compressors were set to 7.5 ms, while the release times were
set to 500 ms. The motivation for choosing such long release times was to minimize the effects of
compression on ILDs. Combining short attack times with long release times results in minimal
distortion of a signal’s amplitude envelope (Dillon, 2001) and can therefore be expected to better
preserve ILDs. Furthermore, the noise reduction system was disabled as it could have distorted
salient spatial cues (Keidser et al, 2006). All but one hearing aid was equipped with a 1.4 mm
collection vent, the single exception being necessary because of one ear canal that would only
accommodate a CIC device with a 1.0 mm collection vent. A further fine-tuning visit was offered
to the subjects to help ensure as comfortable a fitting as possible, but only one subject made use
of that possibility. Following completion of the fitting process, all subjects were allowed to
acclimatize to their new devices for 3-4 weeks prior to any testing.

2.3 Stimuli and procedures

2.3.1 Spatial speech recognition measurements

Speech material

To be able to assess the influence of spatial hearing on intelligibility in speech-on-speech
masking situations, a Danish multi-talker speech corpus was used. This corpus consists of a large
set of Dantale II sentences (Wagener et al, 2003) that all follow the form “name verb numeral
adjective object”. For each syntactic element, there are ten possible alternatives to choose from,
one possible combination being the utterance “Michael had eight yellow houses”. All sentences
were spoken with normal vocal effort by each of five trained female talkers. The recordings of
these sentences were stored as 44.1 kHz, 16 bit sound files, and were adjusted to have the same
RMS level and roughly the same length. The resultant sentences were then tested for their
homogeneity in terms of speech intelligibility, leading to the selection of three talkers and six
names (to be used as “call signs”; cf. below) that produced the most homogeneous performance (Behrens et al, 2008). On any given trial, the sentences presented were mutually exclusive and differed from the previous presentation.

**Physical test set-up**

All spatial speech recognition measurements were made under anechoic conditions. Four active Genelec 8030A loudspeakers were positioned in the horizontal plane at 0°, ±50° and 180° (cf. Figure 3). The distance from the loudspeakers to the listening position was about 1.6 m. A flat-panel computer screen mounted below the frontal loudspeaker was used for displaying instructions. The subject was seated in a custom-made chair equipped with a head rest that was small enough not to obstruct sound reaching the subject’s ears from behind. The chair was adjusted as necessary to ensure that the subject’s head was located precisely at the centre of the test set-up and that the subject was seated comfortably. The subject was instructed to move as little as possible whenever measurements were being made. This was also cross-checked by the experimenter with the help of a video monitoring system. The experimenter controlled the measurements from outside the anechoic chamber by means of customized software that was used to adjust the signal levels as well as to play them back via a multi-channel sound card (Echo Layla). The outputs from the sound card were directly routed to the loudspeakers. In absolute terms, the set-up was calibrated such that the simultaneous presentation of three equal-level speech signals from the front loudspeaker produced a sound pressure level of 65 dB SPL at the listening position. In relative terms, all of the loudspeakers were calibrated to be within ±0.25 dB SPL of each other. In order to keep the overall reproduction level relatively constant, positive
target-to-masker ratios (TMRs) were accomplished by means of a negative masker gain coupled
with a 0-dB target gain, whereas negative TMRs were accomplished in the opposite manner.

Spatial test conditions

Spatial speech recognition measurements were made with three testing arrangements of target
and maskers: (1) co-located, (2) displaced front-back (F-B) and (3) displaced left-right (L-R) (cf.
Figure 3). In the co-located condition, three speech signals were presented simultaneously from
the frontal loudspeaker. One of the signals served as the target and the other two as maskers. Due
to the use of highly similar talkers, the (relatively) synchronous presentation of three same-syntax
sentences and the lack of spatial differences, the dominant cue available to the subjects to
complete this task was the level of the target relative to the level of the maskers, as indicated by
other research (e.g. Brungart et al, 2001; Ihlefeld & Shinn-Cunningham, 2008; Marrone et al,
2008b). In the displaced F-B condition, the target was again presented from the frontal
loudspeaker while the maskers were presented from the rear loudspeaker. Because of making
both target and masker level adjustments (cf. above), randomizing the resultant TMRs (cf.
below), blocking the spatial test condition (cf. below) and choosing a spatial configuration that
ensured near-zero target and masker ITDs and ILDs, the dominant cues available in this condition
were high-frequency monaural spectral cues, which the subjects potentially could exploit to
separate the target from the maskers. In the displaced L-R condition, the target was presented
from the frontal loudspeaker, while the two maskers were presented from the left and right
loudspeaker, respectively. Note that with the two maskers being arranged symmetrically relative
to the listening position, the benefits of (monaural) better-ear listening were minimized (e.g.
Marrone et al, 2008b). The dominant cues available in this condition to segregate the target signal were therefore interaural spatial cues, since, similar to the monaural spectral cues in the displaced F-B condition, they were consistent within a block of measurements, whereas the level of the target relative to the level of the maskers varied in a random fashion. To enable the subjects to identify the target signal, the first word of the target sentence (the name) served as a call sign and was displayed constantly on the computer screen in front of them. The subjects were told that the target would always be presented from the frontal loudspeaker, and before each block of measurements they were also informed about the location of the maskers (and therefore the spatial configuration). Apart from the spatial configuration, the call sign was also held constant within a given block of trials to further reduce task variability. The subjects’ task was to repeat all five words of the target sentence, which the experimenter then entered into the customized software. Note, however, that the scores corresponding to the call signs were excluded from the analyses and that each of the following four words was scored individually. It is also worth pointing out that, because the three talkers were qualitatively very similar to each other and because all of the uttered sentences had the same structure, the test conditions were likely characterized by large amounts of informational masking (e.g. Brungart et al, 2001).

Training

Before the start of the test trials, all subjects went through a training program that took about 1.25 hours to complete. This was intended to familiarize them with the task and to lead to an asymptote in performance. The design of the training program was based on a gradual build-up of the task complexity as well as the provision of feedback (Neher et al, 2008). Training elderly
hearing-aid users in this manner had previously been found to reduce intra-subject variability in such measurements considerably.

Estimation of speech recognition and spatial release from masking

For each of the three spatial test conditions, the target-to-masker ratio (TMR) corresponding to 50%-correct speech intelligibility was estimated. These measurements will be referred to as SRT\textsuperscript{Co-loc}, SRT\textsubscript{F-B} and SRT\textsubscript{L-R} for the co-located, the displaced F-B and displaced L-R conditions, respectively. Note that the two maskers were always presented at the same level and that a 0 dB TMR corresponded to the target, the first masker and the second masker all having the same presentation level individually. Each 50%-correct TMR was extracted from a psychometric function that had been derived using the method of constant stimuli. To begin with, in order to get an indication of where each subject’s threshold was likely to lie, a block of 30 trials was performed per spatial test condition that covered a comparatively large TMR range (suitable ranges were indicated by previous studies). A given TMR was held constant for three trials, after which one of the other (pre-determined) TMRs was randomly chosen. The data from the $3 \times 30$ trials were then used to derive first estimates of the psychometric functions with the help of a maximum-likelihood estimation procedure. From these functions, a few suitably placed TMRs were extracted and another sequence of $3 \times 30$ trials was run. Using the data from the 60 trials per spatial test condition, the psychometric functions were then once more estimated and the final SRTs calculated. Since such spatial speech recognition measurements are typically reported in terms of spatial release from masking (SRM), the SRT\textsubscript{F-B} and SRT\textsubscript{L-R} estimates were also
subtracted from the $SRT_{Co-loc}$ estimates in order to obtain SRM estimates along either the front-back ($SRM_{F,B}$) or the left-right ($SRM_{L,R}$) dimension.

2.4 Cognitive tests

As evident from a recent survey of studies that have investigated possible links between speech reception and cognition (Akeroyd, 2008), cognitive skills are important when trying to understand speech under challenging conditions. Even though this link has generally been found to be secondary to the predictive effects of hearing loss, it should be noted that most studies have used noise as the interfering signal and have also neglected the influence of spatial cues. It could therefore be that cognition plays a larger role under more complex listening conditions.

To investigate the role of hearing-aid users’ cognitive abilities in spatially complex speech-on-speech masking situations such as the ones tested in this study, two types of cognitive tests were employed: the reading span test and the test of everyday attention. Each test is briefly described below. More detailed descriptions of the actual tasks given to the subjects and the types of scores obtained can be found in the appendix.

2.4.1 The reading span test

The reading span test is a visual test of working memory capacity that involves both memory storage and processing (Baddeley et al, 1985; Daneman & Carpenter, 1980). Previous research has shown performance on the reading span test to be correlated with hearing-aid users’ speech recognition in unmodulated background noise (Lunner, 2003). It was therefore included in this
study to investigate if it could also predict the subjects’ hearing abilities in more realistic listening situations.

### 2.4.2 The test of everyday attention

The test of everyday attention (TEA) consists of eight auditory, visual or audio-visual sub-tests that measure different kinds of attention, i.e. selective attention, sustained attention and switching attention, as well as working memory capacity (Robertson et al, 1996). It was included in this study because of recent research findings that have highlighted the importance of being able to attend to a target signal in spatially complex speech recognition tasks (Kidd, Arbogast, Mason & Gallun, 2005).

Originally, the TEA was developed for diagnosing attention problems in subjects suffering from brain damage such as stroke patients. As part of an evaluation of the TEA with 154 normal (i.e. non-brain damaged) subjects ranging in age from 18 to 80 years, sub-tests 2 and 8 were found to exhibit ceiling effects (Robertson et al, 1994). For that reason, only the other sub-tests were used in the current study to investigate the connection between cognition and performance on the various speech recognition tests employed.

### 2.5 Dantale II

In addition to measuring speech recognition in the presence of two competing talkers, speech-in-noise measurements were made using the Dantale II test (Wagener et al, 2003). The Dantale II test is based on an adaptive procedure in which the level of a speech signal is held constant at
65 dB SPL, while the level of an unmodulated speech-shaped noise masker is adjusted according to the subject’s performance. The speech and noise signal are presented from a single, frontal loudspeaker that is set up in an audiometric booth, the noise signal being constantly turned on. The speech material used consists of the same sentences as those that were used for the SRM measurements (cf. Section 2.3.1). The subject’s task is to repeat as many of the five words as possible, which the experimenter scores on a word-by-word basis. The procedure returns the SRT, i.e. the signal-to-noise ratio (SNR) at which 50%-correct speech intelligibility is achieved. These measurements will be referred to as $\text{SRT}_{\text{Dantale}}$. Given that the level of cognitive involvement generally increases as listening becomes more effortful (e.g. Pichora-Fuller & Singh, 2006), it was hoped that, together with the other SRT measurements, the $\text{SRT}_{\text{Dantale}}$ data could help shed some light on the role that cognition played in the different test conditions.

3 RESULTS AND DISCUSSION

3.1 Spatial SRT and SRM measurements

Figure 4 displays the SRTs corresponding to the three spatial test conditions as well as the two SRM estimates. In terms of absolute (SRT) performance, the co-located condition has the highest threshold with a mean of 2.5 dB. In the displaced conditions performance improves, resulting in mean SRTs of –1.1 dB and –2.9 dB for the displaced F-B and L-R condition, respectively. Moreover, while the co-located condition is characterized by homogeneous performance, the $\text{SRT}_{\text{F-B}}$ data range over more than 8 dB and the $\text{SRT}_{\text{L-R}}$ data over more than 14 dB. A one-way repeated-measures analysis of variance showed the effect of spatial test condition to be highly significant [$F(2, 38) = 30.3, p < 0.001$], and a post-hoc (Scheffé) analysis showed all three mean
SRTs to be significantly ($p < 0.05$) different from each other. Expressed in terms of SRM, the subjects received, on average, a 3.6 dB benefit from the availability of front-back spatial information and a 5.4 dB benefit from the availability of left-right spatial information. The spread observable in the SRT measurements is also reflected in the SRM data, SRM$_{F-B}$ ranging over more than 8 dB and SRM$_{L-R}$ over more than 12 dB.

Generally speaking, these results are in good agreement with those from a previous study, conducted with another group of subjects, as part of which a mean SRM$_{F-B}$ of ca. 4 dB (range = ca. 5 dB) and a mean SRM$_{L-R}$ of ca. 6 dB (range = ca. 12 dB) had been obtained (Neher et al, 2008). They are also broadly in line with data from Marrone et al (2008a). Using the coordinate response measure corpus (Bolia et al, 2000) and displacing their two speech maskers to ±90°, Marrone et al also observed little spread in the co-located data from their bilateral hearing-aid users (mean threshold = 5.1 dB, SD = 1.4 dB), whereas their displaced L-R data were characterized by much larger variation (mean threshold = 2.1 dB, SD = 3.9 dB). In addition to their group of bilateral hearing-aid users, Marrone et al tested a group of normal-hearing subjects who obtained 7 dB more SRM$_{L-R}$ than the bilateral hearing-aid users. A similar (ca. 8-10 dB) performance difference, both in terms of SRM$_{L-R}$ and SRM$_{F-B}$, is observable between the data from the current study’s hearing-aid users as well as a group of normal-hearing subjects tested as part of another study (Behrens et al, 2008). It is also worth mentioning that, in contrast to the hearing-aid users, the data from the normal-hearing subjects in (Behrens et al, 2008) exhibited very little spread along the left-right dimension, implying uniform access to left-right spatial information.
In summary, it can be concluded that the SRT and SRM measurements made as part of this study are comparable with other such data. Furthermore, while hearing-aid users perform very similarly in the co-located condition, they differ much more in terms of their ability to exploit front-back, and particularly left-right, spatial information to achieve better speech intelligibility.

### 3.2 Cognitive tests

Table 1 displays the mean and standard deviation data for the various cognitive tests. The reading span data are in very good agreement with other such data (e.g. Lunner, 2003). The TEA results, in turn, can be compared with data published by Gatehouse and Akeroyd (2008) that stem from 76 hearing-impaired subjects aged 42-79 years. Generally speaking, there is reasonable correspondence between the two data sets, some of the differences most probably being due to the larger age span (28-84 years) covered by the subjects from the current study (cf. Section 3.4.2).

In view of the fact that, when evaluating the TEA test with their normal subjects, Robertson et al had observed ceiling effects for some of their sub-tests (cf. Section 2.4.2), all cognitive data were tested for normality with the help of the Shapiro-Wilk’s W test. Except for the data from the reading span test and sub-test 5 of the TEA, the W statistic was found to be significant. This means that for the data from all but one TEA sub-test, the hypothesis that the associated distributions are normal has to be rejected. As a consequence, these data were analyzed using non-parametric statistical tests (cf. Section 3.4.2).
3.3 Dantale II

Concerning the speech-in-noise measurements, a mean SRT\textsubscript{Dantale} of –5.7 dB (SD = 1.5 dB) was obtained. This threshold is very similar to the –5.0 dB mean SRT\textsubscript{Dantale} obtained in another study carried out with a group of hearing-aid users that were fitted with long (640 ms) release times and that exhibited superior performance on a cognitive test measuring aspects of attention, reaction time, continuous performance and working memory (Lunner & Sundewall-Thorén, 2007). In view of the very similar SRT\textsubscript{Dantale} measurements as well as the ceiling effects apparent in the TEA data, it seems likely that the hearing-aid users that took part in the current study also possessed above-average cognitive abilities.

Figure 5 shows a scatter plot of the SRT\textsubscript{Dantale} and SRT\textsubscript{Co-loc} data ($r = 0.68$). Note that the SRT\textsubscript{Co-loc} data have been plotted in terms of SNR (rather than TMR) to make them comparable to the SRT\textsubscript{Dantale} data in terms of the ratio of the energy of the target talker to the energy of the total combined masking signal. As can be seen, performance was generally several dB worse on the co-located task than on the Dantale II task. This implies that the co-located (speech-on-speech) task was more difficult, which was probably due to informational masking effects (cf. Section 2.3.1).

3.4 Correlation analyses

Correlation analyses were carried out in order to better understand the spread in the spatial SRT and SRM data and to explore different factors that might limit the functioning of hearing-aid
users in complex listening situations. One potential predictor variable, which is known to be
related to speech recognition in noise (e.g. Moore, 1998) as well as sound localization accuracy
(e.g. Noble et al, 1994), is the degree of hearing loss. Furthermore, as pointed out in Section 2.5,
the importance of top-down processing is known to increase as listening conditions become more
difficult, which is why age and cognitive function can be assumed to play a role in predicting
performance in spatially complex speech-on-speech masking situations.

3.4.1 Effects of hearing loss

The effects of hearing loss on speech recognition were examined by computing product-moment
correlations between SRT\textsubscript{Co-loc}, SRT\textsubscript{F-B}, SRT\textsubscript{L-R}, SRM\textsubscript{F-B} and SRM\textsubscript{L-R}, and 4FA-HL, 4FA-HL\textsubscript{low},
4FA-HL\textsubscript{high} and 4FA-HL\textsubscript{high\_aided}. The resultant correlation coefficients are shown in Table 2.

There are clear correlations between left-right performance and degree of hearing loss, most
notably in the lower frequencies. More specifically, 4FA-HL and 4FA-HL\textsubscript{low} are positively
correlated with SRT\textsubscript{L-R} and negatively correlated with SRM\textsubscript{L-R}. These correlations make sense in
that performance deteriorates as hearing loss increases. Furthermore, they agree well with the
results from a previous study that had suggested even stronger relationships between both
4FA-HL and 4FA-HL\textsubscript{low} and left-right performance (Neher et al, 2008).

As far as the remaining correlation coefficients are concerned, SRT\textsubscript{Co-loc} and SRT\textsubscript{F-B} are
(positively) correlated with 4FA-HL\textsubscript{high}. In addition, SRT\textsubscript{F-B} is strongly correlated with
4FA-HL\textsubscript{high\_aided}, while the correlation between SRT\textsubscript{Co-loc} and 4FA-HL\textsubscript{high\_aided} is nearly significant
($p = 0.053$). These results imply that access to high-frequency acoustical cues is important in the
co-located and displaced F-B conditions. The correlations disappear when the $SRT_{Co-loc}$ and $SRT_{F-B}$ measurements are expressed in terms of $SRM_{F-B}$. Closer examination revealed that this was due to a number of subjects differing markedly in terms of the degree to which $4FA-HL_{high}$ and $4FA-HL_{high_aided}$ contributed to either type of threshold measurement, resulting in too much spread in the $SRM_{F-B}$ data for the (negative) correlations with $4FA-HL_{high}$ and $4FA-HL_{high_aided}$ to be significant. A possible explanation for this might be that the high-frequency acoustical cues that contribute to either task are different and that the subjects differed in terms of their ability to exploit them (cf. Section 4.2).

### 3.4.2 Effects of age and cognition

Before computing the correlations between age and cognitive function as well as the various SRT and SRM measurements, some of the TEA data were transformed, so that for all cognitive tests a higher score corresponded to better performance (see the appendix for details). Furthermore, the fact that at least 17 of the 20 subjects have a score of seven or higher (out of a possible 10) on the TEA sub-tests 3 and 4 ‘accuracy’ indicates that these data are characterized by strong ceiling effects and therefore exhibit very little spread. Thus, they were excluded from the correlation analyses. Finally, in view of the non-normal distribution of some of the remaining TEA data (cf. Section 3.2) the decision was made to calculate non-parametric Spearman rank order correlation coefficients.

To begin with, it was verified if the well-established decline of cognitive performance with aging (e.g. Salthouse, 1982) was also reflected in the cognitive data collected for the current study, and
from the first row of Table 3 the expected correlations are evident. Table 3 also displays the
correlations between the various SRT and SRM measurements and age and the cognitive tests. In
addition, the SRT$_{\text{Dantale}}$ data have been included to provide a contrast to the speech-on-speech
masking tasks. The first thing to note is that all significant correlations are meaningful in that the
various SRTs are correlated positively with age and negatively with all cognitive scores; for the
SRM measurements the situation is reversed, as would be expected. It is also noteworthy that
correlations generally span across different modalities. Thus, none of the tasks given to the
subjects when performing the various measurements seems to be associated with, for example,
the auditory (cognitive) modality only. As far as possible links between the various test
conditions and different types of cognitive skills are concerned, the SRT$_{\text{Dantale}}$ and SRT$_{\text{F-B}}$ data
are correlated most strongly with the reading span test and TEA sub-test 5, both of which probe
into working memory abilities. The SRT$_{\text{L-R}}$ data, in turn, are correlated most strongly with TEA
sub-tests 1 and 4 ‘timing’, which probe into abilities of selective and switching attention.
Interestingly, all of the other cognitive measures are significantly correlated with SRT$_{\text{L-R}}$, too. For
SRT$_{\text{Co-loc}}$, on the other hand, not a single significant correlation is apparent. This seems to suggest
that the left-right task engaged a broad spectrum of cognitive skills, whereas the co-located task
did not; the front-back and Dantale tasks, in turn, lie somewhere in-between.

Altogether, these results suggest the following: When hearing-aid users are confronted with
multiple similar speech signals coming from different (frontal) directions (as in the SRT$_{\text{L-R}}$
condition), they will benefit from access to a broad range of working memory and attentional
processes when trying to follow one of these signals. When the speech signals are separated
along the front-back axis (as in the SRT_{F-B} condition), working memory processes also appear to play a role; however, attentional processes do not appear as influential. The same seems to hold true when the competing signals are spatially coincident but otherwise qualitatively very different such as speech and unmodulated noise (as in the SRT_{Dantinole} condition). Finally, when the competing signals are both spatially coincident and qualitatively very similar such as three similar speech signals (as in the SRT_{Co-loc} condition), neither working memory nor attentional processes seem to provide any benefit.

### 3.5 Multiple regression analysis

To determine the extent to which hearing thresholds, age and cognitive function are able to predict left-right and front-back performance, multiple regression analyses were carried out. Since running a partial correlation analysis with the effects of age being controlled for had removed all significant correlations between SRT_{L-R} and the cognitive tests, no separate measure of cognitive function was entered into the left-right analyses. As far as front-back performance is concerned, however, the correlation between SRT_{F-B} and the reading span test remained significant after partialling out age effects, which is why reading span performance was included in the front-back analyses.

In terms of predicting SRT_{L-R}, the predictor variables used were age and either 4FA-HL or 4FA-HL_{low} (cf. Table 2). The two models as well as all associated model parameters were found to be highly significant ($p < 0.01$). Furthermore, the model including 4FA-HL_{low} ($R^2 = 0.68$, adjusted $R^2 = 0.64$) was found to be more predictive than the model including 4FA-HL
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\( R^2 = 0.64 \), adjusted \( R^2 = 0.60 \) and is therefore specified further in Table 4. The regression coefficients, \( B \), imply a 2 dB worsening in SRT\(_{L-R}\) for a 10 dB increase in low-frequency hearing thresholds or for a 10 year increase in age, while the standardized regression coefficients, \( \beta \), show that age contributed more to the prediction of SRT\(_{L-R}\) than 4FA-HL\(_{low}\). The model can be tested by using it to predict the difference in SRT\(_{L-R}\) between the current study’s hearing-aid users (mean SRT\(_{L-R}\) = –2.9 dB; mean age = 60 years; mean 4FA-HL\(_{low}\) = 27 dB HL) and the normal-hearing subjects (mean SRT\(_{L-R}\) = –14.2 dB; mean age = 37 years; mean 4FA-HL\(_{low}\) = 0 dB HL) tested in another study (Behrens et al, 2008). Given an age difference of 23 years and a 4FA-HL\(_{low}\) difference of 27 dB HL, the model predicts an SRT\(_{L-R}\) difference of ca. 10 dB, which compares rather well with the 11.3 dB that were actually observed.

In terms of predicting SRT\(_{F-B}\), the predictor variables used were the reading span test and 4FA-HL\(_{high\,\,aided}\) (cf. Table 2). Except for the intercept, all model parameters were found to be significant \((p < 0.05)\), with the model explaining about 65% of the variance (adjusted \( R^2 = 0.61 \)). From Table 4 it is furthermore apparent that reading span performance contributed more to the prediction of SRT\(_{F-B}\) than 4FA-HL\(_{high\,\,aided}\) and that the model predicts a ca. 2 dB worsening in SRT\(_{F-B}\) for a 10 dB increase in 4FA-HL\(_{high\,\,aided}\).

It is interesting to note that, for both SRT\(_{L-R}\) and SRT\(_{F-B}\), the predictor variables representing cognitive impairments (i.e. age and reading span performance, respectively) contributed more to the prediction of left-right and front-back performance than the predictor variables representing peripheral impairments (i.e. 4FA-HL\(_{low}\) and 4FA-HL\(_{high\,\,aided}\), respectively). This is in contrast to
what has typically been observed in studies dealing with the role of cognitive function on speech reception in background noise (cf. Section 2.4) and will be discussed further in Section 4.3.

4 GENERAL DISCUSSION

The aim of this study was to investigate the extent to which bilateral hearing-aid users can take advantage of left-right and front-back spatial cues to achieve release from masking in multi-talker situations, and to obtain a better understanding of how auditory and non-auditory factors might limit their performance in this regard. The approach taken by this study was to determine the spatial benefit achievable by hearing-impaired subjects fitted with, and acclimatized to, CIC devices configured to preserve spatial acoustic cues. In spite of these fittings and the fact that the subjects had very similar audiograms, substantial inter-subject differences in front-back and especially left-right spatial benefit were observed. Subsequent analyses revealed that left-right performance was strongly driven by low-frequency hearing loss, age and a wide range of cognitive skills, whereas front-back performance showed the clearest relationship to high-frequency aided thresholds and working memory capacity.

In the following sections, various aspects concerning the interpretation of the left-right data, the front-back data and the cognitive data will be discussed in more detail. This will then be followed by a separate discussion of how peripheral and cognitive deficits might have affected the spatial benefit obtained by this study’s hearing-aid users.
4.1 Left-right performance

There are a number of issues concerning the $SRT_{L-R}$ and $SRM_{L-R}$ data that warrant further discussion. Firstly, it is worth commenting that left-right performance generally was better than front-back performance. It is widely accepted that normal-hearing and hearing-impaired listeners have better localization acuity in the frontal horizontal plane than in the median vertical plane (e.g. Blauert, 1983; Noble et al, 1994; Noble, Byrne & Ter-Host, 1997). Furthermore, normal-hearing listeners also obtain less benefit from front-back spatial separation than from left-right spatial separation in situations with competing talkers (Freyman et al, 2005). A possible explanation for these findings could be that left-right spatial cues are perceptually more potent and/or robust than front-back spatial cues. For a listener to be able to discriminate along the front-back dimension, signals have to contain sufficient energy above ca. 2 kHz. Speech, however, is generally dominated by lower-frequency energy (e.g. Byrne et al, 1994). What is more, several spatial cues are potentially available to a listener along the left-right dimension, for example ITDs and ILDs. Thus, in relative terms, the left-right test condition should have provided more spatial information than the front-back test condition. Even though better $SRT_{L-R}$ performance could therefore be expected, reduced low-frequency hearing ability was found to restrict the benefit obtainable from left-right spatial separation. One could speculate that this was because the subjects with worse low-frequency hearing thresholds were less able to exploit (low-frequency) ITD cues, which are generally believed to dominate spatial sound perception in environments that are not overly reverberant (Wightman & Kistler, 1992; Kidd, Mason, Brughera & Hartmann, 2005). This speculation is supported by the finding that a sensorineural hearing loss can greatly impair a listener’s ability to detect (low-frequency) ITDs (Buus et al, 1984; Hawkins &
Wightman, 1980; Lacher-Fougère & Demany, 2005). In addition, a connection between low-frequency hearing thresholds and spatial hearing was also reported by Noble et al (1994). More precisely, they observed a correlation of about 0.4 between localization accuracy in the frontal horizontal plane and hearing threshold level at 0.25 and 0.5 kHz for their sensorineurally impaired listeners. This finding agrees well with the correlation of 0.48 observed as part of the current study between SRT$_{L-R}$ and 4FA-HL$_{low}$ (cf. Table 2). Furthermore, based on a review of various studies, Byrne and Noble (1998) concluded that mild (< 50 dB HL) sensorineural hearing losses generally do not lead to a reduced ability to utilize left-right spatial cues for horizontal localization. This finding, however, is not supported by the current results, which were obtained with participants that had a maximal 4FA-HL$_{low}$ of 43 dB HL (cf. Figure 6) and that still showed substantial left-right performance deficits. Nevertheless, it is conceivable that the adverse effects of a low-frequency hearing loss become more pronounced as listening becomes more challenging, for example when a listener tries to understand a talker that is competing with other talkers.

Another aspect that needs to be considered in connection with the SRT$_{L-R}$ results is the fact that the two maskers were acoustically more effective in the displaced L-R condition than in the co-located condition. This is because, relative to 0° sound incidence, the head and pinnae amplify sound coming from 50° by ca. 5 dB more on the ipsilateral side for frequencies higher than 0.5 kHz (cf. Figure 11 in Mehrgardt & Mellert, 1977). This would seem to suggest that the subjects obtained, on average, about 10 dB of spatial release from informational masking that
was offset by about 5 dB more energetic masking, resulting in the measure mean SRM\textsubscript{L-R} of 5.4 dB.

### 4.2 Front-back performance

As pointed out above, it is a consistent finding that both normal-hearing and hearing-impaired listeners localize better in the frontal horizontal plane than in the median vertical plane. Also, subjects with a high-frequency hearing loss are known to be particularly susceptible to front-back confusions (e.g. Noble et al, 1994). This is most likely due to reduced audibility and frequency selectivity, which prevent access to salient monaural spectral cues (Moore, 1998). According to Byrne and Noble (1998), when hearing threshold levels above 4 kHz exceed about 30 dB, sound localization based on monaural spectral cues can already be substantially impaired. This seems to be broadly in line with the current study, which found a group of hearing-aid users with a mean 4FA-HL\textsubscript{high} of 57 dB HL to obtain, on average, limited benefit from front-back spatial separation (cf. below), despite the use of fittings that should have improved the audibility of high-frequency speech sounds (cf. Section 2.2). Therefore, the significant correlation between 4FA-HL\textsubscript{high} and SRT\textsubscript{Co-loc} and the nearly significant correlation between 4FA-HL\textsubscript{high aided} and SRT\textsubscript{Co-loc} probably reflect a reduced ability to discriminate such sounds (rather than a reduced ability to detect them).

In the displaced F-B condition, on the other hand, improved audibility of the target signal should have played a role, since the pinnae shadow high-frequency sound coming from behind (e.g. Mehrgardt & Mellert, 1977; Wightman & Kistler, 1997), leading to TMR improvements at the ears of the listener. In addition to improved TMRs, pinna shadowing results in spatial cues, which a listener in principle can use to separate competing signals perceptually. In contrast to the purely
acoustic (TMR) benefit, this higher-level effect should result in a larger benefit from spatial separation because it allows for spatial focus of attention to take place. To illustrate, when testing a group of normal-hearing subjects on an SRM\(_{F-B}\) task very similar to the one employed in the current study, Freyman et al (2005) found a mean SRM\(_{F-B}\) of 6 dB, of which they attributed 3 dB to better audibility and 3 dB to an improved ability to extract and focus on the target voice.

Furthermore, following an investigation into the relation between aging and speech-on-speech masking, Helfer and Freyman (2008) concluded that older adults, particularly those with a hearing loss, are compromised in their ability to selectively attend to a target message. In view of the fact that the hearing-aid users tested in the current study obtained a mean SRM\(_{F-B}\) of 3.6 dB, it seems likely that many of them could only take advantage of the TMR improvements that occurred in the displaced F-B condition, especially those subjects that suffered not only from peripheral but also higher-level, cognitive deficits.

### 4.3 Cognitive performance

As mentioned in Section 2.4.2, previous research has highlighted the importance of selective attention in spatially complex multi-talker speech recognition tasks (Kidd, Arbogast, Mason & Gallun, 2005). This finding was confirmed by the current study insofar as the displaced L-R condition showed a strong correlation to selective attention abilities. In contrast, the displaced F-B condition was strongly correlated with working memory abilities, but not with selective attention abilities. This finding was somewhat unexpected since in this condition too subjects should have been able to spatially focus their attention, provided they were able to perceptually separate the target from the maskers based on front-back spatial cues. If subjects were indeed
unable to selectively attend to the target and thus to inhibit the maskers, then this should have
posed higher demands for subsequent cognitive processing in terms of parsing the target, and this
might explain the strong correlation to working memory skills that was observed.

It was also found that the different test conditions engaged cognitive function to various degrees.
For example, the displaced L-R condition appeared to engage the whole range of cognitive skills
that were tested. Such general cognitive involvement seems to make sense since, in addition to
having to direct their attention toward the target, subjects were required to remain vigilant for a
prolonged period of time (i.e. for at least 30 trials) as well as to store any target words they could
hear in short-term memory before repeating them at the end of a trial. However, this raises the
question of why such a pervasive cognitive influence was not observed for the other test
conditions, which basically involved the same task. In Section 4.1, it was argued that the
displaced L-R condition was characterized by the presence of perceptually potent spatial cues.
This should have facilitated segregation of the three competing talkers, which, in turn, would
have been beneficial for the ability to direct attention to the target signal (cf. Section 4.4). In
other words, the displaced L-R condition provided the acoustic basis necessary for robust source
segregation, thereby enabling those subjects that could exploit left-right spatial cues to take
advantage of their cognitive abilities. It is also true, however, that in the displaced L-R condition
the two maskers often were louder than the target signal, because the TMRs were frequently
negative and because the subjects’ outer ears provided ca. 5 dB extra masker gain (cf. Section
4.1). As a result, inhibiting the two maskers was a demanding task for the subjects who
informally reported them as being particularly disturbing in this condition. In addition to the
above interpretation, it could be that the large cognitive involvement observed was also driven by a larger mental effort required by those listeners struggling to exploit left-right spatial cues and thus to parse the target signal. This interpretation would seem to be in line with the finding that left-right performance is correlated with low-frequency hearing loss, which was linked to degraded ITD cues in Section 4.1. The possible interpretations of the correlations between cognitive skills and $SRT_{L-R}$ performance outlined above will be discussed further in Section 4.4.

The cognitive skills engaged by the displaced F-B condition were not as wide-ranging as those engaged by the displaced L-R condition. A possible explanation for this could be that the subjects found it harder to spatially separate the target from the maskers based on front-back spatial cues, because these cues were more degraded by the subjects’ sloping hearing losses. That is to say that front-back spatial cues probably did not allow as much for robust target segregation as left-right spatial cues. Indeed, for those subjects that apparently only obtained the acoustic benefit from front-back spatial separation (cf. Section 4.2) the displaced F-B condition would have been more akin to the co-located condition, which showed basically no relation to cognition.

The lack of cognitive involvement in the co-located condition can probably be traced back to a shortage of acoustical information that could contribute to source segregation. As argued in Section 2.3.1, in this condition subjects could basically only rely on a level cue to segregate the target signal, which they first seemed to be able to do once the target was a few dB louder than the maskers (cf. Figure 4). [The same appears to hold true for normal-hearing subjects who perform very similarly on this task (cf. Behrens et al, 2008).] It could be that this level cue is not
as perceptually salient as left-right spatial cues, for example. In any case, it seems that co-located
performance is not limited by top-down skills but rather by the accessibility of high-frequency
speech sounds, as indicated by the observed correlation to high-frequency hearing thresholds (cf.
Table 2).

Finally, the Dantale task, which was included in this study to provide a contrast to the more
complex speech-on-speech masking tasks, was characterized by the presence of very obvious
qualitative differences between the target voice and the unmodulated background noise. It is
therefore conceivable that separating these signals perceptually was dominated by bottom-up
processes. As a consequence, the subjects had to utilize comparatively few cognitive resources to
follow the target message, which would explain the more limited relation to cognition that was
observed.

Another issue that deserves some discussion is the fact that, in contrast to most research that has
dealt with the effects of cognition on the ability to understand speech in the presence of
background noise, this study found factors related to cognitive impairments to be more predictive
of SRT\textsubscript{L-R} and SRT\textsubscript{F-B} performance than factors related to hearing loss (cf. Section 3.5). As
argued above, this was likely due to greater task complexity and hence larger cognitive
involvement caused by the use of speech interferers (and hence the presence of informational
masking) as well as spatial test conditions. Support for this interpretation is available from the
study by Lunner and Sundewall-Thorén (2007; cf. Section 3.3) who showed that their subjects’
performance was driven by hearing loss under relatively simple listening conditions (i.e. in
unmodulated background noise and with slowly varying compression), whereas cognitive abilities drove performance under more complex listening conditions (i.e. in modulated background noise and with fast-acting compression). However, this seems at odds with results from Gatehouse and Akeroyd’s (2008) study that was already alluded to in Sections 2.4 and 3.2. Using a horizontal array of 24 loudspeakers, Gatehouse and Akeroyd required their hearing-impaired listeners to monitor two concurrent lists of sentences, spoken by a male and female talker, for words associated with a certain topic. The sentences were partially masked by continuous background noise, and each sentence was presented from a new, randomly chosen loudspeaker. In addition to that, the listeners had to maintain vigilance for single words that were presented occasionally and that they had to localize and identify. Surprisingly, despite such a demanding task, hardly any significant correlations to the subjects’ cognitive skills (measured with the help of the TEA) emerged.

Nevertheless, as pointed out by Gatehouse and Akeroyd, their study differs from other recent studies into auditory attention in some important ways. For instance, most studies (including the current one) have tried to maximize the confusability of the target and masker sentences by choosing same-sex talkers and by synchronizing the competing sentences. In addition, stimuli have typically been presented on a trial-by-trial basis rather than in a pseudo-continuous manner. This leads to the question of whether the strong influence of cognitive skills that was observed above would be smaller under less contrived conditions, as indicated by Gatehouse and Akeroyd’s results. In this respect, it is worth noting that, as part of another study, Gatehouse et al (2006) found several TEA sub-tests to have substantial predictive power with respect to the self-
reported disabilities of hearing-impaired listeners in perceptually demanding contexts such as multi-talker conversations. All in all, therefore, these results hint at a need for further research into the design of test methods that are more representative of the situations experienced by hearing-aid users. Ideally, this research would then also reveal if the aforementioned experimental factors are indeed responsible for the differences in cognitive involvement observable between Gatehouse and Akeroyd’s (2008) study and this one.

4.4 Effects of peripheral and cognitive deficits

It is a well-known fact that peripheral hearing loss leads to reduced spectro-temporal resolution and hence less detailed encoding of an incoming sound (e.g. Moore, 1998). This, in turn, has been linked to increased amounts of energetic masking that have been observed in sensorineurally impaired listeners (Arbogast et al, 2005). In addition, age-related auditory temporal processing deficits have been reported and related to performance on tests of speech perception, for example loss of synchrony or periodicity coding (see Pichora-Fuller & MacDonald, 2008, for a review). As a direct consequence of all of these effects, the auditory system is less able to extract both lower-order (e.g. common amplitude modulation or harmonic structure) and higher-order (e.g. pitch or perceived location) perceptual features, which are a pre-requisite for source segregation and hence the forming of “objects,” i.e. perceptual entities that are attributed to real, discrete sound sources (Shinn-Cunningham & Best, 2008). In support of this view, Marrone et al (2008b) proposed that for impaired listeners “the images of the stimuli may be less “distinct” than for normal-hearing listeners,” implying that competing sound sources
are not as clearly segregated, which has also been suggested by other studies (e.g. Grose & Hall, 1996; Kidd et al, 2002).

As already touched upon in Section 4.3, the problems associated with peripheral deficits such as the ones outlined above can be expected to cascade upwards to higher-level processes. This is because selective attention (and presumably also other cognitive processes) has been argued to act on objects (Shinn-Cunningham & Best, 2008). Thus, if object formation is less precise, the ability to select and direct attention to objects can be expected to be compromised too, since object selection depends on higher-order features such as perceived location (e.g. Darwin & Hukin, 2000; Kidd, Arbogast, Mason & Gallun, 2005). Listeners experiencing impaired object selection should therefore be less able to filter out competing information, which would then result in a higher potential for informational masking due to greater interference between competing, insufficiently parsed inputs and hence a larger burden being placed on subsequent cognitive processes in terms of recognizing a target (Schneider et al, 2007). Such an increase in cognitive load can be expected to show up particularly in elderly persons who, because of aging effects, are more limited in terms of the cognitive resources they can draw upon (e.g. Pichora-Fuller, 2003, 2006). Nevertheless, there is also evidence that hearing-impaired listeners are able to (partly) compensate for their peripheral deficits by relying on top-down strategies that enable them to fill in gaps and to resolve ambiguities in their degraded sensory input signals. For instance, elderly listeners are known to make use of their preserved “crystallized” cognitive abilities such as a larger vocabulary and world knowledge to counteract declines in “fluid” cognitive abilities such as working memory and reasoning (e.g. Pichora-Fuller, 2008).
The interaction of bottom-up and top-down factors hinted at above seems to be borne out by the data from this study, too. Figure 6 shows a three-dimensional scatter plot of SRT$_{L-R}$ performance, age and 4FA-HL$_{\text{low}}$. Roughly speaking, the data points form a V-like shape, the tip of which is marked by the listeners with the largest low-frequency hearing loss and the highest age. As expected, these listeners were least able to take advantage of left-right spatial cues to achieve release from masking, most probably because of significant deficits in both bottom-up (e.g. ITD encoding) and top-down (e.g. selective attention) processing. Benefit from left-right spatial separation of the three talkers improved, however, with either lower age or milder low-frequency hearing loss. In case of the former, the improvement might reflect better top-down skills, which the younger listeners could rely on to make up for their poorer bottom-up input; in case of the latter, the improvement might reflect more intact bottom-up processes that should have facilitated more precise object formation. These two views of the data are in line with the interpretations, put forward in Section 4.3, of the large cognitive involvement observed for the displaced L-R condition: the less impaired (older) listeners who experienced more automatic object formation could concentrate their cognitive abilities on inhibiting the two masker signals, whereas the more impaired (younger) listeners also had to dedicate cognitive resources to the forming of auditory objects based on left-right spatial cues. Further research would be required to determine if and to what extent these interpretations actually drove the observed correlations between cognitive function and SRT$_{L-R}$ performance.
5  SUMMARY

The purpose of this study was to measure the performance of impaired listeners fitted with hearing aids configured to preserve spatial cues on spatially complex, multi-talker speech recognition tasks, and to determine how performance interacts with hearing loss, age and cognitive function. The analyses showed a clear connection between benefit from left-right spatial separation of three competing, same-sex talkers and low-frequency hearing loss, age and especially attentional but also working memory skills. Furthermore, benefit from separating the three talkers along the front-back dimension was found to be related to high-frequency aided thresholds, age and working memory skills. These findings were interpreted as suggesting that bilateral hearing-aid users are compromised in their ability to understand a target signal in the presence of other talkers because (1) low-frequency hearing loss limits access to ITD cues, (2) high-frequency hearing loss limits access to monaural spectral cues, and (3) reduced access to these spatial cues as well as the effects of aging limit the degree to which top-down processes such as attention and working memory can be drawn upon to “enhance” the signal of interest.

DECLARATION OF INTERESTS

There are no conflicts of interest.

ETHICAL APPROVAL

Ethical approval for the study reported in this manuscript was obtained from “de videnskabsetiske komiteer for region hovedstaden”.

E-mail: editor-ija@utdallas.edu  URL: http://mc.manuscriptcentral.com/tija
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### TABLES

**Table 1.** Mean and standard deviation (SD) for each of the cognitive tests used.

<table>
<thead>
<tr>
<th>Cognitive Test</th>
<th>Mean</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading span (no. of correct words)</td>
<td>23.6</td>
<td>8.6</td>
</tr>
<tr>
<td>TEA 1 (no. of correct symbols)</td>
<td>59.1</td>
<td>18.1</td>
</tr>
<tr>
<td>TEA 3 (no. of correct strings)</td>
<td>7.8</td>
<td>2.9</td>
</tr>
<tr>
<td>TEA 4 ‘accuracy’ (no. of correct floors)</td>
<td>8.2</td>
<td>1.8</td>
</tr>
<tr>
<td>TEA 4 ‘timing’ (secs/directional switch)</td>
<td>4.2</td>
<td>1.6</td>
</tr>
<tr>
<td>TEA 5 (no. of correct floors)</td>
<td>4.4</td>
<td>2.7</td>
</tr>
<tr>
<td>TEA 6 (secs/target symbol)</td>
<td>3.9</td>
<td>1.5</td>
</tr>
<tr>
<td>TEA 7 (dual-task decrement score)</td>
<td>2.0</td>
<td>3.1</td>
</tr>
</tbody>
</table>
Table 2. Product-moment correlation coefficients between $\text{SRT}_{\text{Co-loc}}$, $\text{SRT}_{\text{F-B}}$, $\text{SRT}_{\text{L-R}}$, $\text{SRM}_{\text{F-B}}$, and $\text{SRM}_{\text{L-R}}$, and 4FA-HL, 4FA-HL\text{low}, 4FA-HL\text{high}, and 4FA-HL\text{high}_{\text{aided}}$ (* $p < 0.05$, ** $p < 0.01$).

<table>
<thead>
<tr>
<th></th>
<th>4FA-HL</th>
<th>4FA-HL\text{low}</th>
<th>4FA-HL\text{high}</th>
<th>4FA-HL\text{high}_{\text{aided}}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{SRT}_{\text{Co-loc}}$</td>
<td>0.20</td>
<td>0.02</td>
<td>0.52*</td>
<td>0.44</td>
</tr>
<tr>
<td>$\text{SRT}_{\text{F-B}}$</td>
<td>0.16</td>
<td>0.03</td>
<td>0.47*</td>
<td>0.60**</td>
</tr>
<tr>
<td>$\text{SRT}_{\text{L-R}}$</td>
<td>0.48*</td>
<td>0.48*</td>
<td>0.26</td>
<td>0.34</td>
</tr>
<tr>
<td>$\text{SRM}_{\text{F-B}}$</td>
<td>−0.03</td>
<td>−0.01</td>
<td>−0.15</td>
<td>−0.34</td>
</tr>
<tr>
<td>$\text{SRM}_{\text{L-R}}$</td>
<td>−0.46*</td>
<td>−0.54*</td>
<td>−0.09</td>
<td>−0.21</td>
</tr>
</tbody>
</table>
Table 3. Spearman rank order correlation coefficients between age, $SRT_{Dantale}$, $SRT_{Co-loc}$, $SRT_{F-B}$, $SRT_{L-R}$, $SRM_{F-B}$ and $SRM_{L-R}$, and age and the various cognitive test results (* = $p < 0.05$; ** = $p < 0.01$). For each cognitive test, the test modality [visual (v), auditory (a) or audio-visual (a-v)] and type of cognitive skill [working memory (wm), selective attention (sel), sustained attention (sust) or switching attention (swit)] that it probes into are specified.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>Reading span (v, wm)</th>
<th>TEA 1 (v, sel)</th>
<th>TEA 4 ‘timing’ (v, swit)</th>
<th>TEA 5 (a, wm)</th>
<th>TEA 6 (v, sel)</th>
<th>TEA 7 (a-v, sust+swit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>1</td>
<td>–0.68**</td>
<td>–0.78**</td>
<td>–0.60**</td>
<td>–0.53*</td>
<td>–0.81**</td>
<td>–0.54*</td>
</tr>
<tr>
<td>$SRT_{Dantale}$</td>
<td>0.74**</td>
<td>–0.58**</td>
<td>–0.48*</td>
<td>–0.40</td>
<td>–0.57**</td>
<td>–0.55*</td>
<td>–0.15</td>
</tr>
<tr>
<td>$SRT_{Co-loc}$</td>
<td>0.45*</td>
<td>–0.25</td>
<td>–0.34</td>
<td>–0.20</td>
<td>–0.19</td>
<td>–0.22</td>
<td>–0.22</td>
</tr>
<tr>
<td>$SRT_{F-B}$</td>
<td>0.49*</td>
<td>–0.72**</td>
<td>–0.33</td>
<td>–0.52*</td>
<td>–0.65**</td>
<td>–0.42</td>
<td>–0.12</td>
</tr>
<tr>
<td>$SRT_{L-R}$</td>
<td>0.68**</td>
<td>–0.52*</td>
<td>–0.60**</td>
<td>–0.64**</td>
<td>–0.48*</td>
<td>–0.51*</td>
<td>–0.52*</td>
</tr>
<tr>
<td>$SRM_{F-B}$</td>
<td>–0.20</td>
<td>0.56*</td>
<td>0.19</td>
<td>0.33</td>
<td>0.49*</td>
<td>0.32</td>
<td>–0.03</td>
</tr>
<tr>
<td>$SRM_{L-R}$</td>
<td>–0.61**</td>
<td>0.49*</td>
<td>0.56**</td>
<td>0.66**</td>
<td>0.47*</td>
<td>0.55*</td>
<td>0.47*</td>
</tr>
</tbody>
</table>
Table 4. Multiple regression results with either SRT\(_{L-R}\) \((R^2 = 0.68, \text{adjusted } R^2 = 0.64)\) or SRT\(_{F-B}\) \((R^2 = 0.65, \text{adjusted } R^2 = 0.61)\) as the dependent variable (\(B = \) regression coefficients, \(\beta = \) standardized regression coefficients, \(p = \) significance level).

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>(B)</th>
<th>(\beta)</th>
<th>(p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRT(_{L-R})</td>
<td>Age</td>
<td>0.19</td>
<td>0.67</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td></td>
<td>4FA-HL(_{low})</td>
<td>0.19</td>
<td>0.49</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>SRT(_{F-B})</td>
<td>Reading span</td>
<td>–0.08</td>
<td>–0.58</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td></td>
<td>4FA-HL(_{high_aided})</td>
<td>0.23</td>
<td>0.40</td>
<td>&lt; 0.05</td>
</tr>
</tbody>
</table>
FIGURES

LEGENDS

**Figure 1.** Audiometric data of the test subjects.

**Figure 2.** ANSI speech levels corresponding to an overall level of 65 dB SPL (black, solid line), the target aided thresholds that were set (squares), and the mean (grey, dashed line), minimum and maximum (grey, dotted lines) aided thresholds obtained by the subjects. All data correspond to the one-third octave bands centered at 1, 2, 3, 4 or 6 kHz and are plotted in dB(A) SPL.

**Figure 3.** Physical test set-up and spatial test conditions (T = target, M\(_1\) = masker 1, M\(_2\) = masker 2).

**Figure 4.** Mean and raw data corresponding to the three spatial SRT estimates (SRT\(_{\text{Co-loc}}\), SRT\(_{\text{F-B}}\) and SRT\(_{\text{L-R}}\)) as well as the two SRM estimates (SRM\(_{\text{F-B}}\) and SRM\(_{\text{L-R}}\)), all plotted in terms of TMR. Error bars denote ±95% confidence intervals. The horizontal offset of each subject’s data point is constant across the different SRT and SRM measurements.

**Figure 5.** Scatter plot of SRT\(_{\text{Dantale}}\) and SRT\(_{\text{Co-loc}}\), both plotted in dB SNR.

**Figure 6.** Scatter plot of SRT\(_{\text{L-R}}\), age and 4FA-HL\(_{\text{low}}\). For better clarity, the SRT\(_{\text{L-R}}\) data have been inverted such that a higher position along the z-axis corresponds to better performance.
APPENDIX

This appendix provides details with respect to the tasks given to the subjects when performing the various cognitive measurements as well as the types of scores obtained. Note that, in order to ease interpretation of the correlation results (cf. Section 3.4.2), the signs of the data points stemming from three TEA sub-tests (i.e. sub-tests 4 ‘timing’, 6 and 7) were inverted, so that for all cognitive tests higher scores corresponded to better cognitive performance.

The reading span test

The reading span test (Daneman & Carpenter, 1980; Hällgren et al, 2001) involves the following:

On a computer screen, words are displayed one at a time at a rate of one word per 0.8 seconds. After the presentation of three words there is a pause of 1.75 seconds, during which the subject is asked to respond “yes” if the previous three words made up a semantically correct sentence (e.g. “Pigen børstede håret” – “The girl brushed the hair”). If the previous three words made up a semantically absurd sentence (e.g. “Toget sang sangen” – “The train sang the song”), the test person has to respond “no”. Following a sequence of sentences (three, four, five or six, in ascending order), either “first” or “final” is displayed on the screen. The subject’s task is then to recall either the first or the final words of all the three, four, five or six previous sentences. The performance measure used for this study was the number of correctly recalled first and final words presented.
The test of everyday attention (TEA)

Sub-test 1: Map search

In this visual sub-test of the TEA, the subject is asked to search for and circle as many restaurant symbols on a color map of a metropolitan area as possible. The score obtained is the number out of 80 found within two minutes. According to Robertson et al (1994), this sub-test probes into abilities of selective attention.

Sub-test 2: Elevator counting

As mentioned in Section 2.4.2, this sub-test was found to be affected by ceiling effects in Robertson et al (1994)'s evaluation of the TEA with “normal” (non-brain damaged) subjects. Nevertheless, since it could serve as an introduction to the following sub-tests, a shortened version of it was included in this study, but the scores obtained were not used in the analyses.

Sub-test 2 is an auditory test, as part of which subjects have to imagine being in an elevator whose floor indicator is not working. To establish which floor they are on, they have to listen to and count some strings of tones. According to Robertson et al (1994), this sub-test probes into abilities of sustained attention.

Sub-test 3: Elevator counting with distraction

This auditory sub-test of the TEA builds on the previous one in that strings of tones have to be counted again. This time, however, there are also some distracting, higher-pitched tones. The
subject has to ignore the higher tones and only count the lower ones. The score obtained is how many out of ten strings were counted correctly. According to Robertson et al (1994), this sub-test probes into working memory abilities.

Sub-test 4: Visual elevator

In this visual sub-test of the TEA, subjects are presented with some series of pictures that show either an elevator or an arrow pointing up or down. Each elevator picture represents a separate floor, and the arrows indicate the direction the elevator is moving in. The subjects have to keep track of which floor they are on, reversing the counting direction as necessary. The sub-test is self-paced, and the time taken to complete each picture series is noted. Two types of scores are obtained from the results: (1) an accuracy score reflecting how many (out of 10) final floor numbers the subject got right and (2) a timing score reflecting the total time taken for all correctly counted floor numbers divided by the total number of arrows (directional switches) contained in those series. According to Robertson et al (1994), this sub-test probes into abilities of switching attention.

Sub-test 5: Elevator counting with reversal

Basically, this TEA sub-test is the auditory equivalent of the previous sub-test. The test subject has to count tones, which are presented at a fixed speed, to determine the final floor number. This time, going up is signaled by a high-pitched tone and going down by a low-pitched tone. The tones that represent the different floors and that should therefore be counted have an intermediate pitch. The score obtained is an accuracy score reflecting how many (out of 10) final floor
numbers the subject got right. According to Robertson et al (1994), this sub-test probes into working memory abilities.

Sub-test 6: Telephone search

This visual TEA sub-test involves searching a telephone directory for certain entries such as plumbers, restaurants or hotels. Next to each entry, there are two symbols (stars, squares, circles or crosses). The subjects’ task is to search for certain entries (e.g. plumbers) and circle the two symbols next to them if they are of the same type (e.g. two stars). Moreover, they are told to work as quickly and accurately as possible and to indicate when they are finished. The score obtained is a timing score, corresponding to the total time taken by the subject divided by the number of correctly circled symbol pairs. According to Robertson et al (1994), this test probes into abilities of selective attention.

Sub-test 7: Telephone search while counting

In this audio-visual TEA sub-test, the subject completes the same task as in the previous test. In addition to that, strings of tones have to be counted. Both the timing score from the telephone directory search as well as the proportion of tone strings counted correctly are then computed. By combining these data with the timing scores from the previous sub-test, dual-task decrement scores are obtained, i.e. scores that reflect the cost of having to complete two tasks in parallel. According to Robertson et al (1994), this test probes into abilities of sustained attention, but has aspects of attentional switching to it, too.
REFERENCES


Neher – Spatial Separation Benefit, Hearing Loss, Age and Cognition


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i The Voice Aligned Compression rationale can be classified as curvilinear wide-dynamic range compression that, compared to many other amplification strategies, provides less compression at high input levels and more compression at low input levels through lower compression kneepoints (varying between 30 and 40 dB SPL, depending on frequency region and amount of hearing loss). This compression model is partly based on loudness data by Buus and Florentine (2001) and is intended to ensure improved sound quality without loss of speech intelligibility, rather than loudness compensation *per se*.

ii For a typical sloping hearing loss, ensuring audibility of speech is more difficult in the higher frequencies than in the lower frequencies. This is partly the consequence of worse high-frequency hearing thresholds as well as the spectral properties of speech that lead to larger gain requirements. Nevertheless, it is also of interest to ensure sufficient low-frequency audibility. In a recent study, Moore et al (2008) analyzed the spectro-temporal properties of speech to be able to work out the gains required for (partly) restoring audibility of a 65 dB SPL speech signal in listeners with mild-to-moderate hearing loss. In following their method of calculation and taking vent effects, prescribed gain as well as hearing thresholds into account, it was found that for frequencies below 1 kHz audibility of the RMS level of female speech was achieved for 36 of the 40 ears that were tested; for the other four ears the RMS level around 0.25 kHz was found to be just below the absolute threshold. Hence, even though low-frequency audibility was not verified directly in this study, the subjects’ performance should, in general, not have been limited by inaudibility.
The fact that the reading span test (as well as most subtests of the test of everyday attention) is administered via the visual modality raises the question of whether cognitive abilities can be expected to interact with the modality of presentation. As indicated in Section 1, research into cognitive aging has shown that cognitive abilities generally decline with higher age. More precisely, aging leads to a reduction in “fluid” abilities, which comprise the fast, moment-to-moment processing of information in working memory as well as the inhibition of distracting sensory information via selective attention to the target information (e.g. Pichora-Fuller & Singh, 2006). Furthermore, working memory is widely believed to be a supra-modal cognitive resource (e.g. Reisberg, 2007). While there is evidence for both supra-modal and uni-modal (visual and auditory) attentional resources (e.g. Alais et al, 2006; Driver & Spence, 2004), it seems reasonable to assume that the neurological processes underlying cognitive aging affect these resources equally. All in all, therefore, it is assumed that the cognitive scores collected via the visual modality provide reliable estimates of the cognitive capacities the subjects could draw upon when completing the various listening tasks.

The approach taken by this study was to carry out simple multiple regression analyses with up to two predictor variables in order to comply with guidelines related to sample size and generality of a solution (e.g. Hair et al, 2006; pp. 196-197). The aim was to find the models that were most predictive of the data. As some of the available predictor variables were correlated with each other (e.g. 4FA-HL and 4FA-HL\textsubscript{low}, 4FA-HL\textsubscript{high} and 4FA-HL\textsubscript{high_aided}, or the various cognitive measures and age), other (less predictive) models than the ones reported below could also have been derived.
Co-located

Displaced L-R

Displaced F-B

127x127mm (600 x 600 DPI)
1278x959mm (96 x 96 DPI)