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Retracted Article: Temporal fine structure: relations to cognition and aided speech recognition

Rachel J. Ellis and Jerker Rönnberg

Department of Behavioural Sciences and Learning, Swedish Institute for Disability Research, Linköping University, Linköping, Sweden

ABSTRACT

Objective: The aim of this study was to investigate how sensitivity to temporal fine structure (TFS) correlates with cognitive abilities and speech recognition in adult hearing aid users.
Design: The cognitive tests included measures of working memory and executive function. Aided speech recognition was assessed using an adaptive sentence-in-noise recognition task, and a matrix sentence test presented in two types of noise, using three signal processing strategies.
Study sample: One hundred eighty-nine adults with symmetrical sensorineural hearing loss, and at least one year of hearing aid experience.
Results: After partialling out the effects of age, sensitivity to TFS correlated with the measures of executive function, but not with working memory. While TFS correlated with some of the speech recognition tasks, neither signal processing condition, difficulty, or background noise type affected the degree to which TFS correlated with performance.
Conclusions: The results provide some evidence of an association between TFS and speech-in-noise recognition. That this association was not significantly affected by signal processing strategy goes against the idea that TFS sensitivity is likely to impact on the success of a particular hearing aid signal processing strategy. The results, together with previous findings, suggest a possible link between sensitivity to TFS and visuospatial processing.

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Temporal fine structure; cognition; hearing aids; sensorineural hearing loss; signal processing; speech recognition

Introduction

The goal of this study is to investigate the associations between temporal fine structure, and both cognitive ability and speech-in-noise recognition in adults with hearing impairment.

In order to perceive speech, it is necessary to extract information on both the spectral and temporal components of the signal. Temporal components of speech consist of two sources of information, the temporal envelope and the temporal fine structure. The temporal envelope is the amplitude contour of a signal, whilst temporal fine structure (TFS) refers to the faster fluctuations in the signal relating to phase and frequency.

TFS and cognition

Performances in TFS tests have been shown to correlate with performance on some cognitive tests, but results have been mixed. In a study of 30 adults with normal hearing), TFS sensitivity was associated with performance in the test of everyday attention, and the digit span (forwards and backwards), trail-making test (test B) and block design tests; however, not to the reading span test (Füllgrabe, Moore, and Stone 2015). Neher et al. (2012), based on a sample of 17 adults with hearing impairment found significant correlations between TFS and the map search subtest of the test of everyday attention and reading span test. However, once the effects of age had been partialled out, no significant correlations remained. Lőcsei et al. (2016) also found no evidence of a link between the reading span test and TFS sensitivity in their study of younger adults with normal hearing, and older adults with hearing loss.

TFS and speech recognition

Relatively few studies have looked at the relation between TFS sensitivity and the perception of natural speech ("natural" meaning here that the temporal characteristics of the speech have not been manipulated, see for example Hopkins, Moore, and Stone 2008). Léger, Moore, and Lorenzi (2012) found that, performance in the binaural TFS-LF (at 0.5 kHz but not 0.75 kHz) correlated with low- and mid-frequency VCV recognition in speech-shaped noise in a sample of adults with normal low-to-mid frequency hearing, but there was no link between speech recognition in quiet and sensitivity to TFS (Léger, Moore, and Lorenzi 2012). However, Buss et al. (2004) reported a significant correlation between word recognition in quiet and TFS (measured using a binaural test of frequency modulation) in a study of 12 adults with mild-to-moderate hearing loss.

The majority of studies investigating the relation between TFS and speech recognition have used matrix sentences as stimuli, however, findings have been mixed. Strelcyk and Dau (2009)

CONTACT Rachel J. Ellis rachel.ellis@liu.se Department of Behavioural Sciences and Learning, Swedish Institute for Disability Research, Linköping University, Linköping, 58183, Sweden
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found that both binaural and monaural TFS correlated significantly with speech recognition in two-talker background, or in noise lateralised to one ear, but not with speech presented in amplitude-modulated noise. King et al. (2017) also reported mixed results, finding that monaural TFS sensitivity was significantly correlated with natural speech but only when the target and masker were spatially separated. No significant correlations were found between binaural TFS sensitivity and speech recognition in that study (King et al. 2017). However, Neher et al. (2012) observed a significant association between binaural TFS sensitivity and performance in a test of spatial speech recognition using the same sentence corpus as both King et al. (2017) and Strelcyk and Dau (2009). Both King et al. (2017) and Neher et al. (2012) used a masker of two female talkers. In contrast, Lőcsei et al. (2016) found no evidence of a relation between binaural TFS and matrix sentence recognition in different types of noise, both co-located and separated from the target. Hopkins and Moore (2011) used more predictable sentences as stimuli in their study, finding that monaural, but not binaural, TFS sensitivity predicted speech-in-noise recognition in modulated but not steady noise.

The relative paucity of research, along with the small sample sizes and methodological differences between studies make it difficult to get a clear idea of the effects of TFS sensitivity on speech recognition, or of how this may differ depending on the nature of the stimuli or background noise used, or the cognitive skills of the listener. However, if the effects of TFS on speech recognition are partly related to a more general age-related decline e.g. in temporal or cognitive processing, or processing efficiency (see Kortlang et al. 2016; Moore 2016), it seems reasonable to think that the effects of TFS may be more evident in tasks where cognitive skills can be used to aid performance, that is to say when contextual information, rather than simply auditory information, can be used to aid performance. If this were the case, we would expect TFS to correlate most with high context sentence recognition, than lower context sentence recognition, and least with single word or nonsense syllable recognition. Alternatively, if the effects of TFS on speech recognition are driven primarily by deficits in the auditory system, we would expect to see the opposite pattern of results whereby TFS would be expected to correlate most with single word or nonsense syllable recognition, then lower context sentence recognition, and least with high context sentence recognition.

The results of a factor analysis of a large-scale dataset indicate that temporal processing is associated more strongly with the perception of lower-context speech material than higher context speech material (Rönnberg et al. 2016). This finding provides support for the latter hypothesis. Interestingly, the temporal factor was also associated with a cognitive factor, however, whether this association drove the link between speech recognition and temporal processing is difficult to determine. As the goal of that article was to get an overall picture of the results, only composite measures were used in that study. As such, those results do not allow for the examination of associations between individual tests and conditions, something that is of vital importance if the findings are to be used to inform practice in audiology clinics.

TFS and hearing impairment

Of the studies detailed above, a number of them also looked at TFS sensitivity in listeners with normal hearing. All found that listeners with hearing loss performed more poorly on TFS tests than listeners with normal hearing (Buss et al. 2004; Strelcyk and Dau 2009; Hopkins and Moore 2011; Lőcsei et al. 2016), however, only Hopkins and Moore (2011) controlled for age differences between the participants with normal hearing and the (usually much older) participants with hearing loss. While numerous studies have shown that hearing loss is associated with reduced sensitivity to TFS, the degree of severity of the deficit does not seem to correlate to audiometric thresholds (Hopkins et al. 2008). Furthermore, reduced sensitivity to TFS has been shown to lead to poorer subjective ratings of hearing ability prior to hearing aid fitting, and larger subjective improvements in hearing ability at post-fitting assessments (Perez et al. 2014). Perez et al. (2014) therefore suggest that testing TFS sensitivity prior to hearing aid fitting could provide useful information in terms of predicting, and managing individuals' expectations of, hearing aid outcomes. Further support for the idea that information regarding TFS sensitivity should be considered prior to hearing aid fitting is provided by Moore and Sęk (2016) who found that participants with poorer sensitivity to TFS showed a tendency to prefer slow compression over fast compression (although there was a lot of variation between individuals) and Lopez-Poveda et al. (2017), who found that temporal processing ability predicted aided speech intelligibility in noise in adults with hearing impairment.

TFS and age

Ageing has also been shown to affect sensitivity to TFS, even when audiometric thresholds are within the normal range (Füllgrabe 2013; Füllgrabe, Moore, and Stone 2015), or when the effects of hearing threshold are partialled out (Léger, Moore, and Lorenzi 2012; King, Hopkins, and Plack 2014). However, the relative contribution of age and hearing loss to deficits to TFS processing seems to vary according to whether TFS is processed monaurally or binaurally, with monaural TFS being affected more by hearing loss than age, and binaural TFS being affected more by age than hearing loss (Hopkins and Moore 2011; Moore, Vickers, and Mehta 2012; Moore 2016). Furthermore, there is some evidence to suggest that monaural and binaural tests of TFS may index somewhat different skills, with sensitivity to binaural TFS thought to also reflect binaural processing, resulting in lower thresholds in tests of binaural than tests of monaural TFS (Ewert, Paraouty, and Lorenzi 2018).

Aims of the study

The aim of this study is to investigate how binaural TFS perception correlates with speech-in-noise recognition in different listening conditions (including different signal processing strategies) in a large sample of experienced hearing aid users with mild-to-severe hearing loss. These findings will provide a greater understanding of how, and indeed whether, binaural sensitivity to TFS can be used during hearing screening or hearing aid fitting. We are also interested in how TFS relates to performance in cognitive tests, and whether the pattern of results indicate that temporal processing may mediate the often observed link between cognition and speech recognition. Additionally, we will investigate the effects of age and hearing loss on performance on the tasks, and relations between the variables.

Methods

The data forming the basis of this paper are a subset of those collected as part of the n200 study (see Rönnberg et al. 2016), a large-scale study investigating the links between cognition and speech recognition is listeners with, and eventually those without, hearing loss.

Participants

A total of 215 people were recruited from the University Hospital of Linköping to the initial stages of the n200. For the analyses based on speech recognition, 20 participants were excluded for not having completed the Hagerman test, and 4 more were excluded for not having completed the TFS. Of the remaining 191 participants, 2 were excluded for having performed below chance in the TFS test. For the analyses relating to performance on cognitive tests, 17 participants were excluded for not having completed the TFS, 8 were excluded for not having completed the cognitive tests and 1 more was excluded for having an extremely high score on the inhibition task, which we assume to indicate a lack of understanding of the task. Of the 189 remaining participants, 2 were again excluded for having performed below chance level in the TFS test. Thus the analyses based on speech recognition scores use a sample of 189 participants (33 to 80 years old, with a mean age of 61), and those based on cognitive scores use a sample of 187 participants (27 to 80 years old, with a mean age of 61).

All participants had a symmetrical mild to severe sensorineural hearing loss, and had been fitted bilaterally with hearing aids at least one year prior to testing. For further details of participant demographics, please see Rönnberg et al. (2016).

Procedure

Participants attended three test sessions, during which they completed a number of audiological, cognitive, and speech recognition tests, a subset of which form the basis of the present article and are outlined in detail below. The cognitive tests selected for analysis in this study were chosen to provide one example of a working memory test (the reading span), and three tests of executive functioning (stop-signal inhibition, text reception threshold, Raven's) varying in complexity and the hypothesised relative importance of temporal processing (with Raven's test the least and stop-signal inhibition the most reliant on temporal processing. The selection of the cognitive tests was also motivated by previous research in the field. The reading span test and a block design test (similar to Raven's) have both been previously investigated in terms of their relation to TFS (see Neher et al. 2012; Füllgrabe, Moore, and Stone 2015; Lőcsei et al. 2016), so including similar tests in the current test battery allows for easier comparison of the results.

Pure tone audiometry

Pure tone thresholds were obtained at 0.5, 1, 2, and 4 kHz from both ears. The average loss across all four frequencies and both ears was then calculated. Note that bone conduction thresholds were also obtained, and that any participant with an air-bone gap of greater than 10 dB was excluded from the study.

Temporal fine structure-low frequency (TFS-LF)

The TFS-LF test was developed by Hopkins and Moore (2010), and is a measure of binaural sensitivity to temporal fine structure. An adaptive two-alternative forced-choice procedure was used in which participants were presented binaurally with two intervals, each containing four tones. In each trial, one of the intervals contained an interaural phase shift. The participants' task was to identify which of the two intervals contained this interaural phase shift. Depending on performance, one of two scoring methods was used as recommended by Hopkins and Moore (2010). The primary scoring method was to calculate a threshold in degrees corresponding to 71% accuracy. If performance in the task was poor (indicated by reaching the maximum phase shift possible twice early in the test, or once later), the block was terminated. Forty new trials were then presented in which the maximum phase shift of 180 degrees was used in each trial, allowing a percentage correct score to be calculated. Scores calculated using the percentage correct method were converted to a d prime equivalent to 71% correct, and then extrapolated to give a score in degrees to allow comparison to the standard adaptive scores (see Hopkins and Moore 2010, based on methods by Hacker and Ratcliff 1979; and Hafter and Carrier 1972). This procedure meant that extrapolated scores over 180 degrees indicated performance below chance level. Participants scoring below chance level were removed from further analyses. Participants completed the TFS test twice, and their mean score was calculated and used as the outcome measure.

Stop signal inhibition

The stop-signal task (Logan 1994) is a measure of inhibition that requires participants to press the spacebar every time a new digit appears on a computer screen, except when the number 3 is presented. Participants were asked to respond as quickly and as accurately as possible. Digits were presented for 1 s or until a response was given, with an interstimulus interval of 0.5 s. The outcome measure was the mean error rate (that is, the number of times the spacebar was pressed when a 3 was presented).

Text reception threshold (TRT)

The TRT (Zekveld et al. 2007, 2018) requires participants to read sentences masked by a pattern of bars and has been shown to index executive processes including updating and inhibition (e.g. Mishra et al. 2013) along with lexical access and speeded sentence completion ability (Zekveld et al. 2018). The sentence stimuli were taken from the Swedish HINT test (Nilsson et al. 1994; Hällgren et al. 2006), and were presented word by word in red text on a white background behind a stationary black bar pattern. The bar pattern was varied between trials adaptively, such that a correct response lead to a greater percentage of text in the following sentence being masked. Once the final word had been presented, the whole sentence was visible for 3500 msecs. Participants read the sentence back to the experimenter, who scored a response as correct only when the entire sentence was correctly read. One practice list was administered, and the outcome measure was the average percentage of unmasked text in 16 trials.

Raven's standard progressive matrices

Raven's standard progressive matrices (e.g. Raven 2008) is a paper-and-pencil task that requires participants to pick the missing piece of a pattern from six options. Two sets (D and E) of the test were administered, each set consisting of 12 trials. These two subtests are thought to index analogical reasoning skills and strategy use (Van der Ven and Ellis 2000) or verbal analytic reasoning and visuospatial ability (Lynn, Allik, and Irwing 2004). Set A was used as a practice list, during which the experimenter gave feedback. The outcome measure was the total number of correctly answered trials, out of a maximum of 24. Participants were allowed a total of one hour to complete the task, but no time limit was given at the level of individual trials.

Reading span test

The reading span test (Daneman and Carpenter 1980; Rönnberg et al. 1989) is a measure of complex working memory span, focussing on both processing and storage of information. The test consists of a series of sentences presented visually on a computer screen. The sentences were presented one word at a time at a rate of one word every 800 ms. The sentences presented are always grammatically correct, but half of the sentences are semantically meaningless (e.g. "The fox wrote poetry"). Immediately after having read the sentence, participants are asked to make a yes-no judgement about whether the sentence made sense (processing component). After each block of sentences, participants are asked to recall as many of the first or last word of each sentence as possible (storage component). All responses are typed by the participants, who were asked to respond as quickly and accurately as possible. The number of sentences in a block varies from two-to-five, with two blocks of each length. This gives a maximum score of 28. The blocks were presented in ascending order of difficulty.

HINT

Sentence-in-noise recognition was measured using the Swedish hearing-in-noise test (HINT, Hällgren et al. 2006; Nilsson et al. 1994). The HINT consists of lists of ten everyday sentences (e.g. "The boys played at the beach") presented diotically in stationary white noise. The participants' task was to repeat the sentences back to the experimenter, who scored a response as correct if all words were correctly repeated. The stimuli were processed through an experimental hearing aid, which was programmed with individually prescribed settings to provide linear amplification (see Rönnberg et al. 2016 for details of the device and settings) and played through ER3 insert earphones (Etymotic Research). Both the signal and the noise were initially presented at 65 dB SPL, and the level of the noise was then varied adaptively in 2 dB increments. Participants completed one practice list, and two test lists. The SNR required to achieve 50% correct was then calculated based on the SNRs of the last 15 sentences.

Hagerman test

The Hagerman test (Hagerman 1982) is a Swedish matrix sentence test. Each sentence is five words long and always takes the format of noun-verb-number-adjective-noun (e.g. "Peter bought eight black pens"). The sentences were presented diotically in a background of noise, and the SNRs needed to correctly repeat 50% and 80% of the words were calculated. Responses were scored by the experimenter, who marked a response as correct if all words were repeated by the participant. The initial presentation level was set to 65 dB SPL, with an SNR of 0, and the sentences were varied adaptively using an interleaved procedure tracking both the 50% and 80% performance levels (Brand 2000). In order to investigate the influence of hearing aid settings and noise type, both these features were varied to give three possible signal processing strategies, and two types of background noise. The signal processing strategies were linear amplification only (LA), linear amplification plus noise reduction (NR), and fast-acting nonlinear amplification (NA). The background noise was either unmodulated speech-weighted noise or multi-talker babble. Stimuli were again processed using an experimental hearing aid and presented through ER3A earphones (Etymotic Research). Further details of the signal processing algorithms can be found in Rönnberg et al. 2016).

Results

Prior to analysis, the data were examined to determine whether the assumptions for parametric testing were satisfied. The TFS scores were not normally distributed, thus all subsequent correlations and partial correlations are calculated using Spearman's rank, and descriptive statistics are presented in terms of the median and interquartile range (IQR). All reported p values are based on two-tailed significance, and include a Bonferroni correction to correct for multiple comparisons. Analyses were conducted using IBM SPSS statistics v24.

TFS and the relation to cognition

Descriptive statistics are shown in Table 1, and correlations/partial correlations are presented in Table 2.

A significant positive correlation was observed between TFS score and participants' age, yet not between TFS score and PTA. As such, all subsequent correlation analyses are supported by partial correlations controlling for the effects of age.

Correlations between TFS score and performance on each of the cognitive tests showed r values between −0.165 (TRT, the weakest) and −0.361 (inhibition, the strongest). Again, performance in each of the cognitive tests was correlated with age (with r values between 0.240 and −0.351) such that poorer performance in each of the cognitive tests was associated with increasing

Table 1. Descriptive statistics for TFS (threshold in degrees), age (years), PTA (dBHL), and performance in the reading span (number correct), Raven's (number correct), stop-signal inhibition (number errors), and TRT (% unmasked text).

	Median	Interquartile range
TFS	27.1	16.2 to 58.4
Age	63	58 to 66
PTA	39.4	32.5 to 45.3
HINT	−1.7	−2.7 to −0.7
Hagerman		
LA		
SSN		
50	−6.3	−7.2 to −5.3
80	−2.4	−3.9 to −0.3
4TB		
50	−1.0	−2.2 to 0.2
80	3.6	1.6 to 5.4
NR		
SSN		
50	−11.3	−12.4 to −10.5
80	−6.3	−7.9 to −4.0
4TB		
50	−7.9	−9.1 to −7.0
80	−2.7	−4.6 to −0.7
NA		
SSN		
50	−6.0	−7.0 to −4.9
80	−0.8	−3.2 to 1.4
4TB		
50	−0.4	−1.6 to 0.8
80	4.4	2.7 to 6.6

Table 2. Correlations and partial correlations between TFS, age, PTA, and performance in the cognitive tasks.

	Correlation with TFS, *p* value (two-tailed)	Correlation with age, *p* value (two-tailed)	Partial correlation (age removed) with TFS, *p* value (two-tailed)
TFS	n.a.	$r = 0.270$, $p < 0.001$	n.a.
Age	$r = 0.270$, $p < 0.001$	n.a.	n.a.
PTA	$r = 0.079$, $p = 0.282$	$r = 0.236$, $p = 0.001$	$r = 0.016$, $p = 0.828$
HINT	$r = 0.169$, $p = 0.020$	$r = 0.253$, $p < 0.001$	$r = 0.108$, $p = 0.140$
Hagerman			
LA			
SSN			
50	$r = 0.272$, $p < 0.001$	$r = 0.341$, $p < 0.001$	$r = 0.199$, $p = 0.006$
80	$r = 0.122$, $p = 0.094$	$r = 0.254$, $p < 0.001$	$r = 0.057$, $p = 0.435$
4TB			
50	$r = 0.247$, $p = 0.001$	$r = 0.239$, $p = 0.001$	$r = 0.195$, $p = 0.007$
80	$r = 0.253$, $p < 0.001$	$r = 0.273$, $p < 0.001$	$r = 0.193$, $p = 0.008$
NR			
SSN			
50	$r = 0.259$, $p < 0.001$	$r = 0.264$, $p < 0.001$	$r = 0.202$, $p = 0.006$
80	$r = 0.280$, $p < 0.001$	$r = 0.198$, $p = 0.006$	$r = 0.239$, $p = 0.001$
4TB			
50	$r = 0.285$, $p < 0.001$	$r = 0.327$, $p < 0.001$	$r = 0.216$, $p = 0.003$
80	$r = 0.186$, $p = 0.010$	$r = 0.289$, $p < 0.001$	$r = 0.117$, $p = 0.109$
NA			
SSN			
50	$r = 0.191$, $p = 0.009$	$r = 0.298$, $p < 0.001$	$r = 0.120$, $p = 0.102$
80	$r = 0.192$, $p = 0.008$	$r = 0.272$, $p < 0.001$	$r = 0.127$, $p = 0.081$
4TB			
50	$r = 0.218$, $p = 0.003$	$r = 0.347$, $p < 0.001$	$r = 0.137$, $p = 0.060$
80	$r = 0.177$, $p = 0.015$	$r = 0.275$, $p < 0.001$	$r = 0.111$, $p = 0.130$

Table 3. Differences between correlations with TFS in the different cognitive tasks.

	Hagerman				
	LA	NR	NA	80%	4TB
HINT	$z = 0.79$, $p = 0.431$	$z = 1.32$, $p = 0.0.188$	$z = 0.25$, $p = 0.799$		
NR	$z = -0.59$, $p = 0.556$		$z = 1.17$, $p = 0.244$		
NA	$z = 0.68$, $p = 0.497$				
50%				$z = 0.78$, $p = 0.437$	
SSN					$z = -0.12$, $p = 0.906$

age. After partialling out the effects of age, only performance in the Raven's test correlated significantly with sensitivity to TFS.

In order to check whether there were any significant differences in the correlations between TFS and the cognitive measures (after partialling out the effects of age), the data were further analysed using the methods outlined by Steiger (1980) using software created by Lee and Preacher (2013). These analyses are based on transforming the r values to z scores, and computing a z-test to examine significant differences between pairs of dependent correlations. The results are shown in Table 3. The results showed that only the correlations between TFS and the reading span test, and TFS and Raven's were significantly different from one another.

TFS and the relation to aided speech recognition

Descriptive statistics are shown in Table 4, and correlations/partial correlations are presented in Table 5.

A significant positive correlation was observed between TFS score and participants' age, however, the correlation between the severity of the participants' hearing loss (as measured using PTA) and TFS score was not significant. Given the significant relation between TFS and participants' age, all subsequent correlation analyses are again supported by partial correlations controlling for the effects of age.

Table 4. Descriptive statistics for TFS (threshold in degrees), age (years), PTA (dBHL), and performance in the Hagerman (SNR 50% and 80%) and HINT (SNR 50%) tasks.

	Median	Interquartile range
TFS	27.1	16.2 to 63.0
Age	63	58 to 66
PTA	39.4	32.5 to 45.6
Reading span	15	14 to 19
Raven's	16	13 to 19
Inhibition	1	0 to 3
TRT	54.6	52.1 to 57.7

Descriptive statistics (Table 4) indicate that participants obtained better scores in the NR condition of the Hagerman test than in the LA or NL settings. The results also suggest that participants performed more poorly when the Hagerman sentences were presented in four talker babble, than when they were presented in speech-shaped noise.

Yumba (2017) report the results of an ANOVA analysis of this data (albeit based on 194 participants, instead of the 189 that this article is based on), showing main effects of both signal processing condition and noise, such that performance in the NR condition was significantly better than performance in the other two conditions, and better performance in the speech-shaped noise condition compared to the four talker babble condition. There was a significant interaction effect, which post hoc tests revealed to indicate that there was no effect of noise in the NR condition (see Yumba 2017 for further details of these analyses).

Correlations between the TFS and performance on the various conditions of the Hagerman test are shown in Table 5, and show r values between 0.079 and 0.285. Performance on the HINT, and in all conditions of the Hagerman test were significantly correlated with age (with r values between 0.198 and 0.347), such

Table 5. Correlations and partial correlations between TFS, age, PTA, and performance in the Hagerman and HINT tasks.

	Correlation with TFS, p value (two-tailed)	Correlation with age, p value (two-tailed)	Partial correlation (age removed) with TFS, p value (two-tailed)
TFS	n.a.	$r = 0.284$, $p < 0.001$	n.a.
Age	$r = 0.284$, $p < 0.001$	n.a.	n.a.
PTA	$r = 0.077$, $p = 0.294$	$r = 0.240$, $p = 0.001$	$r = 0.010$, $p = 0.894$
Reading span	$r = -0.165$, $p = 0.024$	$r = -0.351$, $p < 0.001$	$r = -0.073$, $p = 0.321$
Raven's	$r = -0.361$, $p < 0.001$	$r = -0.294$, $p < 0.001$	$r = -0.303$, $p < 0.001$
Inhibition	$r = -0.221$, $p = 0.002$	$r = -0.256$, $p < 0.001$	$r = -0.160$, $p = 0.029$
TRT	$r = 0.216$, $p = 0.003$	$r = 0.246$, $p = 0.001$	$r = 0.158$, $p = 0.031$

that increasing age was associated with poorer performance in every task.

After partialling out the effects of age, performance on the TFS task was still significantly correlated with three of the four conditions of both the LA and NR, but not with any of the NL conditions of the Hagerman, or with the HINT.

The data were again analysed using the methods outlined by Steiger (1980), and detailed above, to investigate whether correlations between the TFS and each of the speech-in-noise measures (after partialling out the effects of age) were significantly different. These analyses are presented in Table 6. The results suggest that neither signal processing condition (LA, NR or NA), background noise (SSN or 4TB), or difficulty level (50% or 80%) influence the extent to which the outcomes correlate with the TFS. Furthermore, there were no significant differences in the extent to which the TFS correlated with performance in the HINT compared to each of the three signal processing methods used in the Hagerman test.

Table 6. Differences between correlations with TFS in the different speech-in-noise tests and conditions.

	Raven's	Inhibition	TRT
Reading span	$z = -2.56$ $p = 0.010$	$z = -0.86$ $p = 0.389$	$z = -1.02$ $p = 0.309$
Inhibition	$z = 1.50$ $p = 0.132$		$z = 0.02$ $p = 0.984$
TRT	$z = 1.91$ $p = 0.056$		

Results are compared across one dimension (signal processing strategy/difficulty/background noise type), they are averaged across all other dimensions (e.g. when comparing correlations based on signal processing type, data from both difficulty levels and both background noise conditions are included in the analyses).

Discussion

The results of the study show that sensitivity to TFS correlates with age, but not with degree of hearing impairment (indexed by pure tone average thresholds at 0.5, 1, 2, and 4 kHz). Performance on each of the four cognitive tests (reading span, stop-signal inhibition, TRT, Raven's) correlated with TFS sensitivity. Only the correlation between Raven's and TFS sensitivity remained significant even after the effects of age were partialled out. After partialling out the effects of age, TFS correlated with the majority of conditions in the Hagerman matrix sentence test using linear amplification only, or noise reduction, however, not with any of the fast compression conditions, nor with performance on the HINT. Subsequent analyses revealed that there were no significant differences in how signal processing, background noise, or difficulty influence the relation matrix sentence recognition to TFS. Nor were there significant differences in how TFS related to matrix sentence recognition in each of the three signal processing conditions and to sentence recognition in the HINT.

The relation of TFS to age and hearing loss

The findings indicate that there is no influence of severity of hearing loss on TFS sensitivity. This is consistent with the majority of previous studies that have investigated the relation between TFS sensitivity and audiometric thresholds (e.g. Hopkins, Moore, and Stone 2008). However, it should be noted that in this study we have only investigated whether there is an effect of severity of hearing loss on TFS sensitivity, rather than whether people with hearing loss tend to have poorer TFS sensitivity than those without (which would be expected based on previous research e.g. King et al. 2014).

In addition to investigating the effects of severity of hearing loss, we also investigated the influence of ageing on sensitivity to TFS. Based on previous literature (see, Füllgrabe 2013; Füllgrabe et al. 2015), we would expect to find a significant effect of aging on performance in the TFS task, particularly since we used the TFS-LF test which is a measure of binaural TFS sensitivity thought to be more affected by ageing that performance in monaural TFS tests (Moore 2016). Our results were consistent with these studies, and ageing was significantly associated with performance on not only the TFS task, but on each of the tasks we assessed.

Depending on performance in the TFS test, scores were either expressed as a threshold in degrees or as a percentage correct (with poorer performance). Percent correct scores were then transformed to allow them to be analysed together with the threshold scores. It is possible that scores based on the two methods are nor really directly comparable even after transformation. In order to overcome difficulties associated with participants being unable to complete the standard version of the TFS-LF test, Füllgrabe et al. (2017) have developed a modified version of the test which all tested participants (Füllgrabe et al. 2017; Füllgrabe and Moore 2017) were able to complete. This may be promising for use in future research.

The relation of TFS to cognition

The findings show that, once the effects of age have been partialled out, sensitivity to TFS correlates significantly to performance in Raven's test of progressive matrices, but not to performance in the reading span test, the TRT or the stop-signal inhibition task. To our knowledge, of these measures, only the relation between the reading span test and TFS sensitivity has been previously investigated. Our findings are consistent with those that have previously reported (Neher et al. 2012; Füllgrabe et al. 2015; Lőcsei et al. 2016) finding no evidence of a significant correlation between the reading span and TFS sensitivity once the effects of age have been partialled out.

Of the four cognitive tests included in this study, Raven's test of progressive matrices is arguably the one least dependent on temporal processing, given that neither the presentation of stimuli nor responses are timed. This seems to point away from a purely temporal basis for these effects. However, it could be that some participants found the overall time limit of one hour to be demanding, thus, it is possible that some participants found the Raven's task to be more temporally-dependent than others.

It is thought that Raven's test measures different skills depending on which subtests are used (Van der Ven and Ellis 2000; Lynn, Allik, and Irwing 2004). The two subtests used in this study (D and E) are thought to index either analogical reasoning skills along with strategy use (Van der Ven and Ellis 2000) or verbal analytic reasoning and visuospatial ability (Lynn, Allik, and Irwing 2004). Previous research on the relation between TFS sensitivity and cognition has reported significant correlations (after partialling out the effects of age) between TFS and performance on the digit span, trail making test (test B), block design, and for the visual elevator and map search subtests of the test of everyday attention (Füllgrabe, Moore, and Stone 2015; however, note that Neher et al. 2012 found no evidence of a link between the latter two measures and TFS). Each of these tasks clearly involve visuospatial processing, with the possible exception of the digit span. However, there is evidence that visuospatial processing is implicated in digit span tasks, particularly the digits backwards test (e.g. St Clair-Thompson and Allen 2013). Taken together, it seems that tasks relating to visuospatial ability seem to correlate the most strongly with tests of TFS, however, the mechanisms behind this link are as yet unclear.

The relation of TFS to aided speech recognition

In the present study, we investigated the relation between TFS sensitivity and performance on two aided sentence-in-noise recognition tasks, the HINT and the Hagerman. The HINT test is an open-set sentence recognition task, higher in contextual cues than the Hagerman test which is a closed-set matrix sentence recognition task. The results showed that while TFS sensitivity correlated significantly with performance on the HINT, once the effects of age were accounted for, the correlation was no longer significant. The Hagerman test was presented in three different signal processing conditions (linear amplification only, linear amplification plus noise reduction, fast compression), two noise backgrounds, (speech shaped noise, four talker babble), and two difficulty conditions (50% and 80% SNR). TFS sensitivity correlated with performance in every condition of the Hagerman test, however, once the effects of age had been partialled out, all correlations became weaker, particularly the correlations between TFS and performance in the fast-compression condition. Neither signal processing strategy, difficulty or background noise type affected the degree to which TFS correlated to performance in the Hagerman test. Together, these results provide evidence that while there may be a relation between TFS and speech in noise recognition, there is a lot of variability and it is not consistently affected by noise type, task difficulty, signal processing, or degree of contextual information (at least in the particular conditions employed in this study).

Thus, these results do not clearly support (or arguably contradict) either a processing efficiency, general temporal processing, or auditory-only based explanation of the link between speech recognition and TFS. To our knowledge, no previous study has investigated whether signal processing strategy affects the relation between TFS sensitivity and speech in noise recognition, however, Moore and Sęk (2016) reported that older adults with poorer TFS sensitivity are more likely to prefer slow compression than those with better sensitivity to TFS. In this study, we did not collect data on subjective preferences for signal processing strategies, but it would interesting for future research to further investigate the relation between subjective and objective outcome measures.

Previous studies investigating the link between TFS and objective speech in noise recognition in listeners with hearing loss have often observed either limited (e.g. Léger et al. 2012) or no significant link (e.g. Lőcsei et al. 2016) between the two. While the results of the present study seem to provide stronger evidence for such a link, there was no clear evidence for the idea that amount of contextual information may affect the degree to which sensitivity to TFS correlated with speech recognition.

Furthermore, it should be noted that the results of this study are based on performance in a binaural test of TFS sensitivity. There is some evidence to suggest that monaural and binaural TFS tests differ in the extent to which they are associated with different auditory processing tasks (e.g. Lopez-Poveda et al. 2017; Ewert, Paraouty, and Lorenzi 2018). Monaural processing of TFS is important for recognising speech in background noise and perceiving pitch, while binaural TFS is important for localising sound and obtaining benefit from the binaural masking level difference (see Moore 2016 for a review). Thus, it may be that a different pattern of results would have been observed had we used a test of monaural TFS sensitivity, or speech tasks in which the role of spatial processing was emphasised.

Clinical implications

Previous studies have found links between TFS sensitivity and subjective ratings of hearing ability and hearing aid benefit (Perez et al. 2014), and preference for slow versus fast compression (Moore and Sęk 2016). These results suggest that it may be beneficial to consider sensitivity to TFS prior to hearing aid fitting. However, the results of the present study show that signal processing strategy does not significantly affect the relation between TFS and speech-in-noise recognition. This suggests that sensitivity to TFS is unlikely to impact on the relative success of a given signal processing strategy over another (as opposed to overall success from a hearing aid), at least in terms of the signal processing strategies and speech recognition measures included in this study.

Conclusions

The results of the study provide evidence for an association between sensitivity to TFS and aided speech in noise recognition in listeners with hearing loss. However, no evidence was found to support the idea that signal processing, task difficulty, contextual information or type of background noise affect this link. An analysis of the relation between TFS and performance on a cognitive test battery was consistent with previous research in finding no evidence of a link between TFS and working memory. However, the findings, taken together with previous research, suggest a possible link between performance on the TFS test and visuospatial ability. Further research is needed to determine the mechanisms behind this link.

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ORCID

Rachel J. Ellis http://orcid.org/0000-0002-6874-9785
Jerker Rönnberg http://orcid.org/0000-0001-7311-9959

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