# Temporal Fine Structure and Working Memory Abilities on Deciding the Probable Compression Speed in Hearing Aids

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## Highlights

- Good TFS benefits from fast compression; good WM supports any speed
- The results suggest that except for good TFS and WM, slow speed is recommended
- The proposed clinical framework helps choose compression speed

## ABSTRACT

**Background and Aim:** Temporal fine structure (TFS) sensitivity and working memory (WM) abilities have been widely studied individually as the contributing factors for deciding compression speed in hearing aids.The study aimed to develop a clinical framework for setting optimal compression speed using combination of TFS sensitivity and WM abilities.

**Methods:** Participants were 25 native Kannada-speaking adults (Mean age 70 years). We evaluated the participant's TFS sensitivity using the TFS -adaptive frequency (-AF) and WM abilities using reading span test. Further, aided sentence recognition in noise was tested to obtain find the signal-to-noise ratio 50% (SNR50) correct identification happens in fast acting compression (FAC) and slow acting compression (SAC) modes.

**Results:** Individuals with good TFS sensitivity demonstrated significantly lower SNR50 scores with FAC and individuals with poor WM showed significantly lower SNR50 with SAC. However, individuals with poor TFS sensitivity and individuals with good WM ability showed no significance on SNR50 obtained between FAC and SAC. A strong negative correlation existed between TFS sensitivity and SNR50 in both SAC and FAC modes even after accounting for WM abilities. There was a mild negative correlation between WM abilities and SNR50 in FAC mode only, but this was not significant after accounting for TFS sensitivity.

**Conclusion:** Using the results of the present study along with the literature findings, a clinical framework was devised to enable the selection of appropriate compression speed for optimal speech understanding with hearing aids.

**Keywords:** release time, amplification, speech in noise, elderly, hearing-impaired

## Introduction

Hearing aids (HAs) are auditory prostheses designed to assist individuals with sensorineural hearing loss (SNHL) through various processing techniques. Compression speed determines the speed of compression, i.e., fast-acting compression (FAC) and slow-acting compression (SAC) (1). Speech perception in hearing-impaired individuals is influenced by age, degree of hearing loss, ability to process envelope and fine structure cues, WM abillity and hearing aid parameters such as number of channels, release time and compression ratio (2). This study assessed the effect of WM abilities and Temporal Fine Structure (TFS) sensitivity on speech understanding in noise from FAC and SAC.

Compression speed in hearing aids is classified as slow-acting or fast-acting based on the compression release time. Release time is how long it takes for the hearing aid to return to linear mode following a sudden decrease in sound intensity. SAC provides slower gain changes, preserving temporal envelope cues, without amplifying low-level sounds and FAC quickly adjust gain even for soft sounds, but reduces the contrast between low and high-intensity sounds (3).

Studies on FAC and SAC effects on speech perception have mixed results. Gatehouse et al. (4) reported good speech intelligibility with FAC but preferred SAC for listening comfort. Moore et al. (5) reported better speech intelligibility in noise with SAC. Davies-Venn et al. (6) reported higher distortions with FAC, degrading performance at conversational and high intensity levels. Hansen (7) showed better speech quality and intelligibility with SAC in both normal hearing and hearing impaired individuals. Moore et al. (8) found poorer identification scores with SAC in quiet and no difference between SAC and FAC in noise. Moore and Sek (9) reported a clear preference towards SAC for music and speech perception. Zhang et al. (10) developed a protocol using modulation discrimination thresholds, speech recognition in noise (SRT 75%) and action potential recording to select FAC and SAC in presbycusis patients. They reported that the protocol can select the compression speed with 90% accuracy and SAC yielded better modulation discrimination thresholds and lower SRT 75%. Variability observed from the above literature could be due to differences in stimuli, tasks, hearing loss severity and cognitive abilities of participants.

TFS sensitivity in hearing-impaired individuals is crucial for determining speed of compression (9,11), as benefits vary with the individuals' ability to utilise TFS cues background noise (12). Individuals with poor TFS sensitivity rely on temporal cues, since FAC disrupts these cues, SAC is preferred for them (12), and FAC for individuals with good TFS abilities (13). However, Hopkins et al. (11) found that preserving TFS cues did not affect sentence recognition in noise for normal hearing individuals with simulated hearing loss. Thus, individuals with good TFS sensitivity may benefit from both FAC and SAC.

WM abilities also influence the choice of compression speed. Gatehouse et al. (14) reported that individuals with poor WM performed well with SAC, and good WM individuals with FAC. Similarly, Souza and Sirow (15) reported that FAC benefits individuals with high WM, but SAC is unrelated to WM abilities. Studies have shown that FAC negatively affects speech perception in poor WM individuals (16,17), as it is harder to FAC-processed signals with the stored lexicon (18). Cox and Xu (19) emphasized on appropriate selection of compression speed for individuals with decreased cognitive abilities. Their results showed that SAC yielded better speech recognition with low semantic context and that clinical speech in noise measures or cognitive abilities did not accurately predict preferred compression speed.

The above mentioned studies have separately utilized either TFS sensitivity or WM to determine hearing aid compression speed, yielding mixed results and complicating clinical decisions. Can combining both TFS and WM measurements assist clinicians in selecting the optimal compression speed for hearing aids? This study aimed to explore the combined impact of TFS sensitivity and WM on determining compression speed to improve speech recognition in noisy environments and to establish clinical guidelines for selecting compression speed based on both factors.

## Methods

A block randomised factorial correlational research design was used to determine the complex interaction of peripheral processing and WM to decide the compression speed in hearing aids in older individuals with hearing loss.

## Subject selection

A total of 25 participants aged 60 to 80 years (mean 70.87± 6.40 years) with post-lingual acquired bilateral symmetrical mild to moderately severe gradual sloping (6 -10 dB per octave decrement) SNHL without prior experience of hearing aid usage and self-reported hearing loss was less than two years were recruited using purposive sampling. All participants were native kannada speakers with graduate-level education and no history of neurological and otological problems.

A sample size of 23 was recommended based on the study by Salorio-Corbetto et al. (20) considering the speech recognition with FAC Mean (SD) = 57 (5); and SAC Mean (SD) = 53 (6). For round off, a sample of 25 was selected.

**Procedure**
An informed consent was obtained from all the study participants before they were enrolled for the study. All the participants were evaluated on the following tests.

**Working memory assessment**
Reading span test was administered to assess WM abilities using Smriti-Shravan 3.0 software (21). It comprises two tasks, the primary task was to indicate if the sentence was semantically correct and then read the bi-syllabic target word. The secondary task was to recall the target words which were presented along with non-target words in free recall order when indicated by a beep sound. The total score was obtained by averaging the correctly recalled words by the total number of target words presented. The results were obtained in Percentage of Correct Score Weightage (PCSW) ranging between 0 and 1 (value nearing one indicates good WM abilities).

**Temporal processing ability assessment**
Temporal fine structure-adaptive frequency (TFS-AF) developed by Fullgrabe and Moore (22) is a test to determine a person's sensitivity to TFS below 1400 Hz. The ability to compare the phase of sinusoidal tones between the two ears to identify a change in interaural phase difference (IPD) is assessed in this test. There are two blocks of stimuli, each containing four tones either with the same interaural phase difference or with phases different by $180^0$. The stimulus duration was 400 ms, including 20-ms onset and offset ramps. A two-interval, two-alternative forced-choice task was used. The stimulus was presented through headphones binaurally at 30 dB SL.
The client was instructed to indicate the interval (1 or 2) in which the sound appears to move within the head. After eight reversals, the run was terminated, and the geometric mean of the frequency at the last six reversal points was used to calculate the TFS threshold in Hz (Figure 1). If the SD is greater than 0.2, considerable variability is inferred, and the measurement is repeated (22).

**Programming of hearing aids**
Bilateral commercially available RIC hearing aids having the option of setting the compression speed to either FAC or SAC were selected. Hearing aids were programmed to acclimatization level 1 using NAL-$NL_2$, which assigned compression threshold and ratio automatically. Features of the hearing aid, including noise reduction, directional microphone and feedback cancellation, were not activated, and the release times in FAC mode varied between 5 to 200 ms and in SAC between 300 to 2000 ms. The release time of FAC and SAC was 125.5 ms and 1220.75 ms, respectively. The attack time was 3.5 ms for both FAC and SAC. In electro-acoustic coupler measurements, each attack and release time were within 50 %, as specified by ANSI S 3.22-2014 (23). Real ear measurement was carried out using Fonix 8000 hearing aid analyzer to confirm that the hearing aid output matched with the prescribed target within 3 to 4 dB across frequencies between 200 to 6400 Hz.
**A**
**ssessment of speech perception in noise**
**Stimuli:** Two standardised list of low-predictive sentences developed by Geetha et al. (24) mixed with speech-shaped noise at different signal-to-noise ratios (SNR) from +12 dB to -6 dB in 2 dB steps was used to assess speech perception in noise by calculating SNR 50. The generation of speech-shaped noise is provided elsewhere (25). Each list consisted on ten sentences with 4-5 target words in each sentence. Two sets of 10 target stimuli were mixed with noise using AUX viewer software to assess the SNR 50 in fast and slow compression settings.
SNR = wave (filename) @rms >> 500 + ramp (wave (noise) @rms, 20)
The sentence mixed with speech-shaped noise were randomly presented through speakers placed one meter away from the client at 0-degree azimuth at 65 dBSPL in FAC and SAC conditions. The participants were instructed to repeat each word of the sentence heard. For all the different SNR levels, the initial starting level (L) of the test and the total number of words correctly recognised from all ten sentences (T) of a list was noted. The total number of words tested at each level (W) and SNR step difference (d) were noted down. The Spearman-Karber equation (26) mentioned below was used to determine SNR 50.

$$\text{SNR } 50 = [L + (0.5 \times d) - (d \times T)/W]$$

**Statistical analysis**

Non-parametric statistics were used due to non-normal data distribution ($p<0.05$). Wilcoxon signed-rank test compared SNR 50 scores between individuals with good and poor TFS sensitivity and those with good and poor WM abilities. Spearman correlation assessed the relationship between TFS sensitivity and SNR 50 scores in FAC and SAC conditions, with partial correlation accounting for WM. Similar correlations were conducting between WM and SNR 50 scores, partialling out TFS sensitivity.

## Results

### Effect of temporal fine structure sensitivity on signal-to-noise ratios 50 obtained in fast and slow acting compression

The mean TFS score was 200.24 $\pm$ 50.6 Hz. Participants with TFS score of >150 Hz were considered to have good TFS sensitivity ($n=10$) and those <150 Hz had poor TFS sensitivity ($n=15$). Good TFS participants had lower (better) SNR 50 scores than poor TFS participants in both FAC and SAC conditions (Table 1). Statistical analysis showed significantly lower SNR 50 scores in FAC than SAC for individuls with good TFS ($Z = -2.818$, $p = 0.005$). For participants with poor TFS, although SAC required a lower than FAC to reach 50% recognition, the difference was not significant ($Z = -1.328$; $p = 0.184$).

### Effect of working memory abilities on signal-to-noise ratios 50 obtained in fast and slow acting compression

The mean reading span score was 0.70$\pm$ 0.11. Those with scores of > 0.59 were considered to have good WM, and < 0.59 were classified as having poor WM. From table 2 it can be observed that individuals with good WM had better (lower) SNR 50 than those with poor WM in both FAC and SAC conditions. Statistical analysis revealed no significant difference in SNR 50 scores between FAC and SAC for good WM participants ($Z = -1.929$, $p = 0.054$). However, the poor WM participants had significantly lower SNR 50 scores in SAC than in FAC ($Z = -2.214$, $p = 0.027$).

### Relationship between temporal finse structure sensitivity and signal-to-noise ratios 50 in fast and slow acting compression

The Spearman correlation revealed a strong negative correlation between TFS scores and SNR 50 in both FAC ($N = 25$, $r = -0.862$, $p < 0.001$) and SAC ($N = 25$, $r = -0.783$, $p < 0.001$). This indicates that individuals with higher TFS lower SNR to reach 50 % recognition in both conditions (Figure 2 A and B). This significance persisted even after accounting for WM abilities: FAC ($N=25$, $r=-0.740$, $p<0.001$) and SAC ($N=25$, $r=-0.642$, $p<0.001$) (Figure-3 A and B). Thus, TFS ability strongly contributes to speech understanding in noise, independent of WM (Table 3).

### Relationship between working memory and signal-to-noise ratios 50 in fast and slow acting compression

The Spearman correlation showed no correlation between SNR 50 and WM ability in SAC ($N = 25$, $r = -0.303$, $p = 0.140$). In FAC, a mild negative correlation was observed ($N = 25$, $r = -0.418$, $p = 0.038$) (Figure-4). This correlation lost significance after accounting for TFS abilities ($r=-0.324$, $p=0.123$). Overall, WM alone did not significantly influence SNR 50 scores (Table 3).

## Discussion

The study aimed to develop a clinical framework for setting compression speed based on TFS and WM abilities, enhancing speech understanding in noisy environment. The results are discussed in relation to possible combination of TFS sensitivities (good and poor) and WM abililities (good and poor).

### Good temporal fine structure sensitivity with good working memory ability

Individuals with good TFS sensitivity showed significantly lower SNR50 scores with FAC than SAC. Higher TFS values correlated with SNR 50 scores in both compression speeds but stronger with FAC. However, the difference in SNR 50 scores between FAC than SAC was not significant for those with good WM. FAC is recommended for individuals with good TFS and WM abilities due to its rapid gain adjustments that enhances audibility especially for consonants following intense vowel sounds (13). Individuals with good WM can process the rapidly changing temporal fine structure than their counterparts, and FAC has been considered to preserve TFS cues in the dips, which is crucial for speech perception (27,28).

**Good temporal fine structure sensitivity with poor working memory ability**
Individuals in this group had poor WM with better SNR50 scores with SAC compared to FAC and presence of good TFS sensitivity warrants FAC. This creates a dilemma for this group. Analysis shows a strong negative correlation of TFS with SNR50 in both the conditions (FAC, r = -0.862; SAC, r = -0.783), suggesting that those with good TFS may perform well with SAC also. Individuals with poor WM perform better with SAC due to its ability to maintain envelope and inability of FAC to maintain consonant-to-vowel ratio (17,29). The Ease of Language Understanding (18) model suggests that listeners with poorer WM are negatively affected by FAC eventhough it improves audibility, it does not preserve the envelope cues (30,31). Further, SAC is preferred as it provides extra time to process the information and allocate resources effectively. Based on the results of this study and others, it is appropriate to choose SAC for individuals with good TFS sensitivity and poorer WM abilities (Table 4).

**Poor temporal fine structure sensitivity with good working memory ability**
Individuals with poor TFS sensitivity exhibited no significant difference in SNR50 scores between SAC (Median=4 dBSNR), and FAC (Median=5 dBSNR) conditions. Similarly, individuals with good WM also showed no significant difference in SNR50 scores between the two conditions. Correlation between WM and SNR50 was mild with FAC, and partial correlation revealed no significant relation. This indicates that TFS sensitivity has a greater influence than WM towards speech understanding in noise. Cox and Xu (19) suggested that individuals with good WM do not have a preference for particular compression speed. However, those with poor TFS sensitivity rely mainly on temporal envelope to understand speech (32,33) and have difficulty detecting and interpreting rapid changes (34). SAC is preferred for these individuals, as it preserves the temporal envelope of speech by changing the gain less often (9). Combining these findings with previous studies, SAC is recommended for individuals with poor TFS sensitivity and good WM ability (Table-4).

**Poor temporal fine structure sensitivity with poor working memory ability**
Participants with poor TFS sensitivity did not show significant differences in SNR50 scores between FAC and SAC, even though scores were better with SAC. Individuals with poor WM abilities showed significant improvement in SNR 50 scores with SAC compared to FAC.
Various studies have reported the importance of TFS sensitivity in determining compression speed. FAC fails to preserve envelope cues, reducing speech understading in multitalker situations for individuals with poor TFS sensitivity (33,35). Thus SAC is more suitbale for these individuals (12).
With limited WM, the resources for listening task are inadequate especially in noisy situation (36). FAC's rapid gain changes burden limited cognitive resources (30,31). SAC preserves the temporal envelope of speech by changing gain less often, providing longer processing time and helping allocate resources effectively. Hence, SAC is recommended for individuals with poor TFS and WM abilities (Table 4).

**Conclusion**
The current study supports the consideration of both TFS sensitivity and working memory (WM) abilities when choosing the compression speed in hearing aids, particularly in relation to speech recognition in noisy environments. Integrating these measures into a clinical framework can assist clinicians in selecting an optimal compression speed. For instance, individuals with good WM and TFS may benefit from fast-acting compression, while those with poor WM and good TFS may require slower compression. Similarly, those with good WM but poor TFS may also benefit from slower compression. However, individuals with poor WM and TFS may require the slowest compression. Nonetheless, further research is recommended to validate this framework, potentially by varying the speech rate.

**Author Contributions:**
VK: Study design, interpretation of results, statistical analysis and drafting the manuscript; JJ: acquisition of data and drafting the manuscript; HNS: Interpretation of the results, supervison, statistical analysis and critical revision of the manuscript

**Declaration:** Not applicable

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**Informed consent:** Informed consent prior to the evaluation after briefing about the study was taken from all the participants.
**Ethical Statement**
**Compliance with Ethical standards:** The research is compliant with ethical standards according to the 1964 Helsinki declaration. The research was approved by JSS Institutional Ethics Committee (JSSMC/IEC/110523/14NCT/2023-24).
**Declaration of Generative AI and AI assisted technologies in the writing process:**
We have not used AI in the manuscript preparation process.
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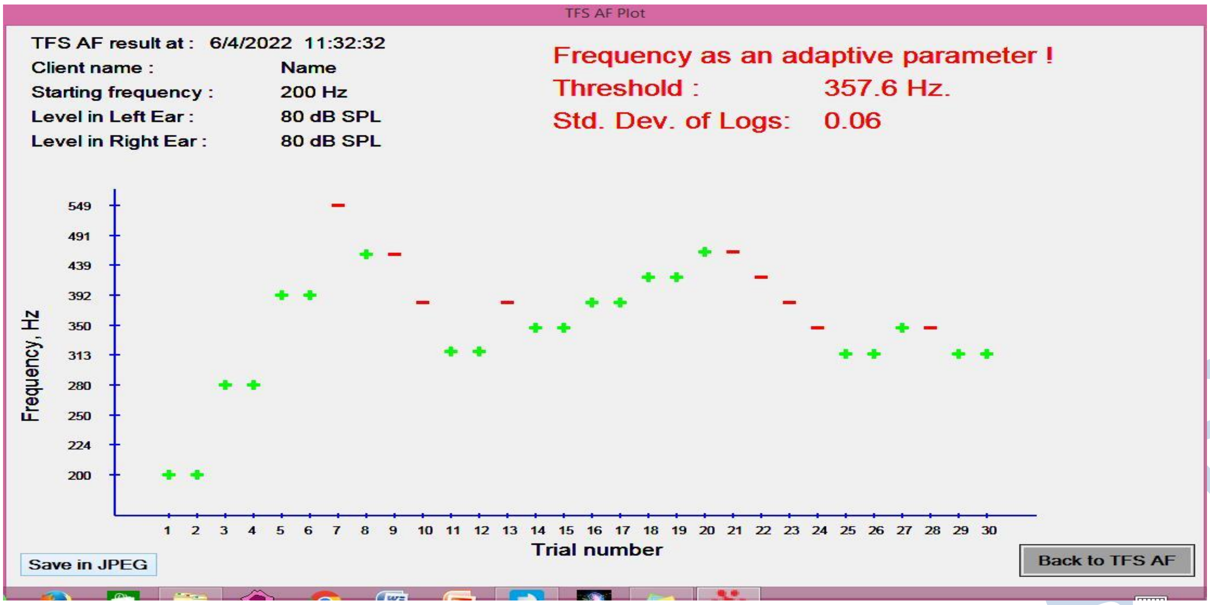


**Figure 1. Sample representation of trials of stimulus presentation and threshold measurement in temporal fine structure adaptive frequency (TFS-AF) test**

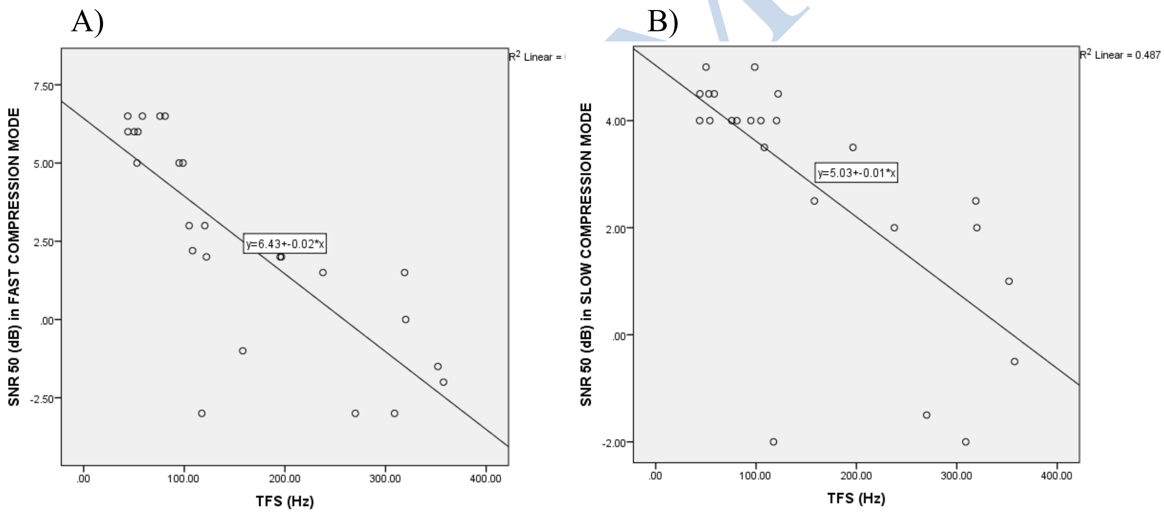


**Figure 2. Scatter plot showing the relationship between temporal fine structure and SNR 50 scores in (A) fast acting compression and (B) slow acting compression**

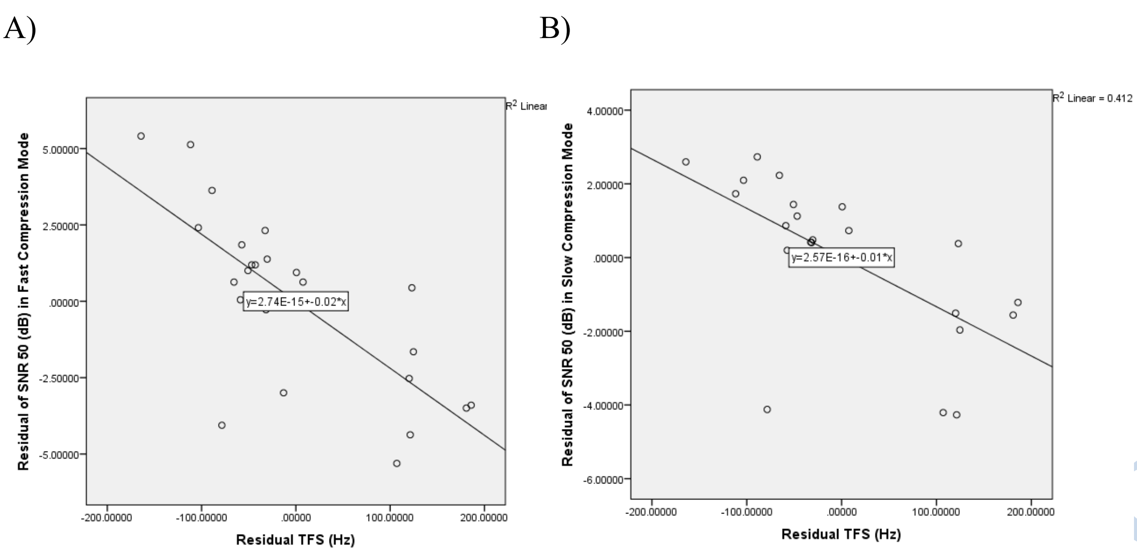


**Figure 3. Scatter plot showing the relationship between residual temporal fine structure and residual after controlling the working memory contribution on SNR 50 scores in (A) fast acting compression and (B) slow acting compression**

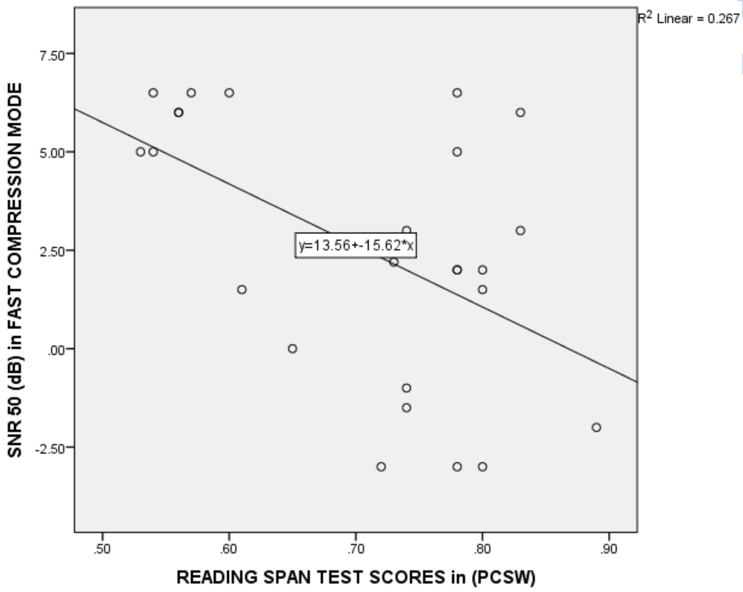


**Figure 4. Scatter plot showing the relationship between reading span test scores and SNR 50 scores in fast acting compression**

**Table 1. Median and interquartile range for temporal fine structure (Threshold in Hz), SNR 50 (signal to noise ratio required to identify 50% of the words correctly) in fast and slow acting compression mode in individuals with good and poor temporal fine structure sensitivity**

| | TFS GOOD (N = 10) | | TFS POOR (N = 15) | |
|---|---|---|---|---|
| | **Median** | **Interquartile Range** | **Median** | **Interquartile Range** |
| **TFS (in Hz)** | 289.45 | 196.17 - 328 | 80.9 | 53 – 108.2 |
| **SNR 50 in fast-acting compression mode (in dB SNR)** | -0.5 | -2.25 - 1.62 | 5 | 3 - 6.5 |
| **SNR 50 in slow-acting compression mode** | 2 | -.075 - 2.62 | 4 | 4 - 4.5 |

TFS-Temporal Fine Structure, SNR-Signal-to-Noise Ratio.

**Table 2. Median and interquartile range for Working memory (in percentage correct score weightage-PCSW), SNR 50 (signal to noise ratio required to identify 50% of the words correctly) in fast and slow acting compression mode in individuals with good and poor WM abilities**

| | WM GOOD (N = 19) | | WM POOR (N = 6) | |
|---|---|---|---|---|
| | **Median** | **Interquartile Range** | **Median** | **Interquartile Range** |
| **Working memory (in PCSW)** | 0.78 | 0.735 – 0.8 | 0.55 | 0.53 – 0.56 |
| **SNR 50 in fast-acting compression mode (in dB SNR)** | 2 | -1.25 – 3 | 6 | 5 – 6.375 |
| **SNR 50 in slow-acting compression mode** | 3 | 1.5 – 4 | 4.25 | 4 – 4.5 |

WM-Working memory, PCSW-Percentage of Correct Score Weightage, SNR-Signal-to-Noise Ratio.

**Table 3 Correlations and partial correlations between SNR-50 in different compression speeds in individuals with good and poor temporal fine strucure sensitivity and working memory abilities**

| | **Correlation with TFS p-value, (2 tailed)** | **Partial correlation with (controlling for WM abilities) TFS p-value, (2 tailed)** | **Correlation with WM p-value, (2 tailed)** | **Partial correlation with (controlling for TFS processing abilities) WM p-value, (2 tailed)** |
|---|---|---|---|---|
| **SNR 50 in FAC mode** | r=-0.862, p=0.001* | r=-0.740, p=0.001* | r=-0.418, p=0.038* | r=-0.324, p=0.123 |
| **SNR 50 on SAC mode** | r=-0.783, p=0.001* | r=-0.642, p=0.001* | r=-0.303, p=0.140 | r=-0.117, p=0.587 |

TFS- Temporal Fine Strucuture, WM-Working Memory, FAC-Fast Acting Compression, SAC-Slow Acting Compression

**Table 4 Summary of recommended compression speed based on temporal fine structure sensitivity and working memory abilities**

| | | Temporal Fine Structure | |
|---|---|---|---|
| | | **Good** | **Poor** |
| **Working Memory** | **Good** | Fast Acting Compression (FAC) | Slow Acting Compression (SAC) |
| | **Poor** | Slow Acting Compression (SAC) | Slow Acting Compression (SAC) |

FAC-Fast Acting Compression, SAC-Slow Acting Compression