Title: Auditory Rehabilitation after Stroke: Treatment of Auditory Processing Disorders in Stroke Patients with Personal Frequency-Modulated (FM) Systems

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Short Title: Personal FM systems in stroke

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Abstract

Purpose**:** Auditory disability due to impaired auditory processing (AP) despite normal pure-tone thresholds is common after stroke, and it leads to isolation, reduced quality of life and physical decline. There are currently no proven remedial interventions for AP deficits in stroke patients. This is the first study to investigate the benefits of personal frequency-modulated (FM) systems in stroke patients with disordered AP.

Methods**:** Fifty stroke patients had baseline audiological assessments, AP tests and completed the (modified) Amsterdam Inventory for Auditory Disability (AIAD) and Hearing Handicap Inventory for Elderly (HHIE) questionnaires. Nine out of these fifty patients were diagnosed with disordered AP based on severe deficits in understanding speech in background noise but with normal pure-tone thresholds. These nine patients underwent spatial speech-in-noise testing in a sound-attenuating chamber (the "crescent of sound") with and without FM systems.

Results**:** The signal-to-noise-ratio (SNR) for 50% correct speech recognition performance was measured with speech presented from 0° azimuth and competing babble from ±90° azimuth. Spatial release from masking (SRM) was defined as the difference between SNRs measured with co-located speech and babble and SNRs measured with spatially separated speech and babble. The SRM significantly improved when babble was spatially separated from target speech, while the patients had the FM systems in their ears compared to without the FM systems.

Conclusions**:** Personal FM systems may substantially improve speech-in-noise deficits in stroke patients who are not eligible for conventional hearing aids. FMs are feasible in stroke patients and show promise to address impaired AP after stroke.

1. Introduction

The majority of stroke survivors suffer from some type of hearing or auditory processing (AP) impairment [1-3]. Hearing impairment may be pre-existent in the stroke population because age related degeneration of the hearing end organ and nerve is very common with advancing age [4-5] and because 3/4 of stroke sufferers are >60 years old [6]. However, stroke may affect all levels of the auditory pathway and lead to hearing reception and/or perception deficits that may manifest with a variety of symptoms and with clinical presentations that start acutely before, during, or shortly after stroke [7]. Hearing and related communication disability is not limited to those with abnormal hearing thresholds. Aphasia after stroke has been studied extensively, and there is evidence for management strategies for these patients [7-8]. However, there are few empirical studies of AP in non-aphasic stroke survivors [9-10, 1]. In addition, approximately one in five stroke survivors [1] report severe difficulties when listening to speech-in-noise, despite normal pure-tone thresholds. These difficulties are attributed to abnormal processing of sounds within the brain. These individuals are more likely to experience communication difficulties in poor acoustic environments, such as in noisy hospital settings [11]. Uncorrected hearing impairment leads to isolation, reduced quality of life [12] and an increased odds risk (1.83) of poorer physical recovery after stroke [13].

The patient with significant auditory deficits and functional limitations may require a range of rehabilitation and remediation approaches. Nonetheless, use of conventional hearing aids in a case of a stroke patient who has AP will not improve the AP deficit, because manipulation of the sound volume does not necessarily alleviate signal-to-noise ratio (SNR). Despite indications that AP deficits are common after stroke [1,14], there is a lack of evidence-based treatment for such impairments.

Several studies conclusively demonstrate substantial improvements in speech recognition in noise when using personal frequency-modulated (FM) systems [15-18]. In recent years, digital FM systems have become available for audiometrically normal patients with AP deficits [19-22]. In FM systems, a microphone, worn by or placed near to the speaker's mouth, picks up the speech signal. The FM transmitter then converts the speech signal to an electrical waveform and transmits it using FM radio waves to a receiver worn by the listener. The receiver converts the waveform back into acoustic energy and delivers it directly to the listener's ears. These systems help to address the acoustic problem of distance, background noise and reverberation [23]. Moreover, FM systems enhance SNR and overall speech signal audibility.

Studies of children [19-21] with disordered AP and adults with auditory neuropathy [24] have demonstrated that use of the FM systems significantly improve speech perception in noise. No studies to date have assessed the efficacy of personal FM systems for stroke patients with disordered AP. Furthermore, strategies for restoration of auditory processing dysfunction after stroke receive significantly less attention, with auditory rehabilitation being arguably the "lost dimension" of stroke rehabilitation. We conducted a feasibility study in order to investigate whether stroke survivors with normal pure-tone thresholds yet with difficulties hearing speech-in-noise due to disordered AP benefit from the use of binaural FM systems.

2. Methods

The London Queen Square National Health Service Ethics Committee approved this study. Written informed consent was obtained from all participants.

The inclusion criteria were: **a.** adults aged between 18- and 80-years-old **b.** clinical history of a single stroke verified by magnetic resonance imaging (MRI) of the brain **c.** patient reported hearing-in-noise difficulty with z score > 2 on the speech-in-noise subscale of the Amsterdam Inventory for Auditory Disability [25] as per departmental normative data [1] **d.** abnormal performance in the speech in babble [26] and in at least one non-speech auditory processing test [10,27] **e.** pure-tone audiogram (PTA) average (from 500 to 8000 Hz at octave levels) better than 25dBHL. Exclusion criteria were severe aphasia (cut-off of 93.8 on the complete Western Aphasia Battery test [28]), significant psychiatric illnesses, other neurological disorders (except stroke) and severe concurrent medical illnesses.

Phase I: Identification of Participants

Fifty patients with an acute ischemic or haemorrhagic stroke, who had been admitted to the Stroke Units at the University College London Hospitals, were identified as fulfilling inclusion criteria (**a**) and (**b**), and were screened for all exclusion criteria. All patients had baseline tests over a single session, three to twelve months after stroke onset. The timing of these tests is to take into account that auditory deficits can be reversible during the hyper-acute and acute stages of stroke [14]. Ten patients also fulfilled inclusion criteria **a**-**f**, and were invited to participate in the FM feasibility study. One declined due to other research involvement. Nine patients attended the clinic on a second occasion to complete the feasibility study test protocol. Demographic data, disease duration, and description of stroke lesion of the nine study participants are shown in Table 1.

Table 1: Lesion description in the eight recruited stroke patients. M, Male; F, Female

Participant	Age	Sex	Lesion	Disease Duration (Days)
1	64	M	Paramedial right thalamus and left cerebellar hemisphere infarct	100
2	24	M	Left frontal, temporal lobes and insula infarct	169
3	44	M	Right putamen / corona radiata infarct	96
4	52	M	Left medulla oblongata, right cerebellum, left occipital lobe and hippocampal tail infarct	207
5	53	F	Right superior parietal lobule infarct	125
6	32	M	Right temporal lobe infarct	110
7	78	M	Left Occipito-temporal infarct	265
8	64	M	Right temporal lobe infarct	179
9	32	M	Right insula infarct	301

A. *Initial Assessments*

Brain MRI

All participants had a brain MRI performed on a 1.5 Tesla GE Signa scanner (General Electric, Milwaukee, WI) 48 hours after the stroke. The acquisition techniques included T1- weighted three-dimensional fast low-angles shot images for volumetric and morphometric analyses. The scan acquisition parameters were: repetition time = 15 ms; echo time = 5.4 ms; flip angle = 15; inversion time = 650 ms. All scans were reviewed by a consultant neurologist (DW) and a consultant neuro-radiologist (CH) for structural brain abnormalities.

Baseline Audiometry

After otoscopy, hearing thresholds were measured by pure-tone audiometry using a GSI 61 audiometer with TDH-39 headphones [29]. Air-conduction thresholds were measured for each ear at 0.5, 1, 2, 4, and 8 kHz following the procedure recommended by the British Society of Audiology (2011). Normal hearing thresholds were considered ≤ 25 dB HL across the above frequency range. (See supplementary material for results).

B. *Auditory Processing Assessments*

Speech in Babble Test

The Speech in Babble (SiB) test was administered via a custom Matlab software system over Sennheiser (Wedemark, Germany) HD 600 supra-aural headphones in a sound-attenuated room. The target stimuli were monosyllabic phonetically balanced meaningful words spoken by an adult female British English talker. Each word is delivered with 500 milliseconds of 20-talker babble, and the speech volume is varied adaptively. The listener repeats the words heard, and a threshold value is obtained, calculated by the software as the mean SNR of 70.7% correct performance criteria in each ear [26].

Non-Speech Auditory Processing Assessments

1. The gaps-in-noise (GIN) test measures temporal resolution by estimating a gap detection threshold and total percentage correct score [10]. The GIN test compact disk was played on a Sony CD Player and passed through a GSI 61 diagnostic audiometer to TDH-39 matched earphones. The stimuli were presented at 50 dB sensation level (SL) to each ear independently [30].

2. Perceptual Property Processing involves the cortical analysis of perceptual spectral properties [31], which contribute to, but are unlikely in isolation to constitute, whole auditory object representations. The patient has to make a judgement of same or different for each of thirty-two same (sixteen) or different (sixteen) spectral shape sounds pairs. (See Goll et al., 2009).

3. Apperceptive Processing: The key experimental manipulation here is Spectral Inversion (SI) [32], which flips or exchanges the energy present between higher and lower frequencies in a broadband sound about a user-specified frequency value to create a frequency structure that is ‘impossible’ in a natural sound [27]. For this test, forty sounds (twenty non-SI and twenty SI sounds) are presented individually, and for each sound, the participant was asked: ‘Is it a real thing or not a real thing?’.

4. Semantic Processing: Assessments were designed to examine the association of conceptual meaning with environmental sound objects [27]. Thirty-two individual sounds from a range of human, animal and environmental sounds are paired so that the individual sounds in a pair have dissimilar acoustic characteristics to reduce the availability of perceptual matching cues. All 32 sounds appear once in the ‘same’ condition (sounds produced by the same source e.g., horse neighing, horse galloping) and once in the ‘different’ condition (sounds produced by different sources e.g., horse neighing, human coughing).

C. Questionnaires

The (modified) Amsterdam Inventory for Auditory Disability and Handicap (AIAD) [25] consists of 28 items covering five domains (subscales) of everyday hearing ability: intelligibility of speech-in-noise; intelligibility of speech in quiet; auditory localization; recognition of sound; detection of sound. The response range consists of ‘almost always’ (0 point), ‘frequently’ (1 points), ‘occasionally’ (2 point), and ‘almost never’ (3 points) with a higher score denoting higher disability. A subscale score is calculated for each subscale as the sum of scores for questions answered, divided by the number of questions answered for each subscale.

The Hearing Handicap Inventory for Elderly (HHIE) [33] is a 25-item self-assessment questionnaire with thirteen items on emotional aspects (E) and twelve on social and situational communication aspects (S). For each item, participants are asked to give one of the following responses: ‘yes’ (4 points); ‘sometimes’ (2 points), or ‘no’ (0 points). Scores for the total scale range from 0, suggesting no perceived handicap, to 100, indicating significant perceived handicap.

Phase II: Feasibility FM study

All nine stroke patients were fitted with personal FM systems binaurally and were tested with and without the FM systems on a speech (sentence) perception test in the crescent of sound.

A. AB-York Crescent of Sound

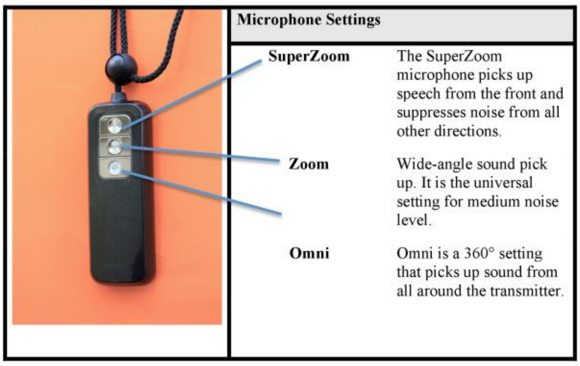
This is a sound attenuated booth with nine audio and seven visual stands, an equipment cabinet, and a testing station for the assessment of spatial-listening skills [34]. The stands are arranged in a semi-circular arc with a radius of 1.45m. Seven stands are separated at 30° intervals, and two additional stands are placed 15° on either side of 0°, where 0° is straight ahead of listening position. The testing station controls the apparatus, including administering listening tests and recording and analysing the responses of participants.

B. Personal FM Systems

The Phonak iSense personal FM systems are designed for individuals with normal/near-to-normal hearing and consist of the iSense Micro (figure 1a) receiver and the ZoomLink+ (figure 1b) transmitter. This device has dynamic FM, which features a proprietary component referred to as the Dynamic Speech Extractor (DSE). The DSE adaptively varies the gain of the FM receiver depending on the level of noise at the microphone of the FM transmitter. In quiet and in noisy environments, when speech is not present at the input of the FM microphone of the Phonak iSense Dynamic FM transmitter, the receiver is muted in an attempt to optimize sound quality. This feature may reduce the audibility of unwanted noise, which may be present in the form of ‘‘static noise’’ or a ‘‘rushing noise’’ that accompanies the primary FM signal. When speech is presented to the FM microphone and ambient noise is less than 57 dB SPL, the default gain of the Dynamic FM receiver is set to +10. When ambient noise levels exceed 57 dB SPL, the gain of the FM receiver is increased by an amount that is proportional to the noise level. The maximum gain of the FM receiver is +24 at a noise-input level of approximately 75 dB SPL [35].

Figure 1a: FM receiver is a lightweight hearing receiver that is worn as one of a pair.

Figure 1b: The Microphone settings of Dynamic FM Transmitter



Microphone Settings	
SuperZoom	The SuperZoom microphone picks up speech from the front and suppresses noise from all other directions.
Zoom	Wide-angle sound pick up. It is the universal setting for medium noise level.
Omni	Omni is a 360° setting that picks up sound from all around the transmitter.

FM technology picks up the voice of the speaker via a body-worn transmitter microphone. It then uses harmless radio waves to send this signal wirelessly to the listener, who wear a hearing receiver.

Figure 1: a) FM receiver is a lightweight hearing receiver that is worn as one of a pair. b) The Microphone settings of Dynamic FM Transmitter

C. Speech Stimuli: Sentences in Noise

In this test, sentences are presented from straight ahead (0°) while noise is coming from the front (0°) or from 90° to the left or right from the participant, who is asked to repeat the sentence. The co-located sentences and noise condition (S0°N0°) was utilized to calculate the spatial release from masking. The number of keywords successfully repeated is recorded, and repetition of at least three keywords per sentence is required to judge correct performance. The level of the sentences and the background noise are adaptively varied to estimate the signal-to-noise ratio (SNR) for 50% correct performance.

D. Speech in Noise Test with and without FM Systems in the Crescent of Sound

The sentences were presented from a loudspeaker positioned at 0° azimuth located 1m from the participant. The microphone of the FM transmitter was placed on a stand, 12 cm from the 0° azimuth loudspeaker. All testing was conducted utilizing a directional microphone.

Each participant completed twelve test runs of the sentences in noise test: 1) Aided condition: Two runs with the noise in each of three positions (straight-ahead 0°; left −90°; right +90°) with bilateral personal FM systems in the ears and 2) Unaided condition: Two similar runs with noise without binaural FM systems. The order of the runs was counterbalanced across participants, and all runs were administered in a single session. No sentence was repeated in order to prevent potential learning effects.

The advantage for speech intelligibility typically observed when the interfering sounds are spatially separated from the target, known as spatial release from masking (SRM) [36-38]. Spatial release from masking shares many properties with localization [39]. Thus, in view of the abnormality in the sound localizing scores of the AIAD questionnaire, SRM was calculated to investigate if there is a better-ear SRM advantage (if the right SRM differs from the left). Measures of spatial release from masking for speech (SRM) [40] can be obtained by calculating the difference in dB between the SNR obtained in a condition where speech and noise are presented from 0°, and a condition where the speech is presented from 0° while the noise is presented from either ±90°. SRM is a measure of the advantage of attending to the ear that is shielded from the noise by the head. We carried out a condition when speech and noise were coming from the front (0°) simultaneously to calculate the SRM for speech.

3. Results

Auditory Processing tests and Questionnaires

Auditory processing test performance is summarized in Table 2. A cross signifies the presence of a deficit judged by performance of more than two standard deviations below the mean according to our departmental normative data. No participant had a semantic type deficit. Of nine stroke patients in our study, six had bilateral and three unilateral abnormality in GIN. Patient numbers 5, 6, and 9 had infarction in the right superior parietal lobule, right temporal lobe and right insula respectively, and all had GIN abnormality on the left ear. SiB were abnormal bilaterally in all patients except patient number 5 who only had an abnormality in the left ear.

The Mann–Whitney U test was used to assess differences in AIAD and HHIE questionnaire scores in patients compared to normative data and to calculate p-values (summarized in Table 3). Patients had significantly worse AIAD questionnaire scores ($p<0.05$) in speech in noise and sound localization sub-scores than normal. The results of emotional, situational and total HHIE scores were also significantly worse in the stroke patients ($p<0.05$) than normal.

Participant #	**GIN**		**Perceptual Property**	**Apperceptive**	**Semantic**	**SiB**	
	Rt	**Lt**				**Rt**	**Lt**
1	+	+	_	_	_	+	+
2	+	+	+	+	_	+	+
3	+	+	_	+	_	+	+
4	+	+	_	_	_	+	+
5	_	+	+	_	_	_	+
6	_	+	+	_	_	+	+
7	+	+	_	+	_	+	+
8	+	+	+	+	_	+	+
9	_	+	+	_	_	+	+

Table 2: Summary of AP Assessment. Cross (+) signifies the presence of a deficit. GIN= Gaps In Noise, SiB= Speech in Babble, Rt= Right, Lt= Left

Scores of AIAD and HHIE questionnaires	**FM group Mean (SD)**	**Normative Data[1, 15] Mean (SD)**	**Mean difference**	**CI of Mean difference**	**p-value**
AAID sound detection	2.8 (2.7)	0.1 (0.3)	2.1	-0.4-5	0.001*
AAID sound recognition	4.2 (4.4)	1 (0.1)	3.2	-0.18-7.9	0.089
AAID speech in noise	8.4 (3.2)	1.8 (2.5)	6.6	4-10.2	0.01*
AAID speech in quiet	3.8 (3.5)	0.1 (0.3)	3.7	-.12-7.2	0.057
AAID sound localisation	5 (3.6)	1 (0.4)	4	1.3-8.1	0.052
HHIE Emotional	7.7 (10)	0.8 (1.5)	6.9	-2.1-17.58	0.03*
HHIE Situational	8.3 (8.3)	0.5 (0.9)	7.8	0.62-15.9	0.02*
HHIE Total	16 (18.1)	1.4 (2.5)	14.6	-.81-32.8	0.01*

Table 3: Results of AAID and HHIE inventory questionnaires compared to normative data. SD= Standard Deviation, CI= Confidence Interval, AIAD= Amsterdam Inventory for Auditory Disability, HHIE= Hearing Handicap Inventory for Elderly

Sentences in Noise With and Without Personal FM Systems

A repeated measures ANOVA was conducted to determine whether there was a statistically significant difference in spatial speech reception with FM use with the noise coming from different angles (90°+ or 90°–).

The FM systems use x angle of noise interaction was significant, F (2,8) = 15.765, p = 0.002, indicating that the SNR scores, when the noise came from the different angles, differed when the patients wore the FM systems compared to when they completed the test without the FM systems. When the noise was coming from the right or left loud speakers, the improvement in the SNR scores was significantly more pronounced when the patients used the FM systems by an average of 9.2 SD 3.4 dB SPL.

Spatial release from masking (SRM) was defined as the difference between SNRs measured with co-located speech and babble (S0°N0°) and SNRs measured with spatially separated speech and babble (S0°N90°+ or S0°N90°–). The SRM was calculated by subtracting the SNR in the 90°+ or 90°– conditions from that in the 0° condition. Table 4 shows the mean SNRs for word recognition in three noise conditions, S0°N0°, S0°N90°+ and S0°N90°–, and the calculated SRM for with and without FM conditions.

	S0°N0°	S0°N90°+	S0°N90°-	SRM90°+	SRM90°-	SRM90°±
Without FM (dB)						
Mean	1.39	-0.1	-0.77	-1.07	-0.62	-1.06
SD	1.44	2.02	2.84	1.89	3.11	1.73
Range	-1.69 – 3.66	-3.63 – 3.43	-2.35 – 0.91	-3.16 – 2.55	-4.41 – 3.84	-3.11– 1.65
With FM (dB)						
Mean	0.97	-9.28	-11.04	-10.25	-12	-11.13
SD	0.94	3.02	2.83	3.4	2.86	2.76
Range	-0.44 – 2.69	-5.37 – -14.60	-15.67 – -6.63	-16.29 – -6.46	-16.55 – -7.27	-15.58 – -7.09

Table 4: Mean, standard deviation and range of SNR (dB) measured in the S0°N0°, S0°N90°+, and S0°N90°– location, and the calculated SRM for with and without FM conditions.

Participants completed two runs of aided condition and two runs of unaided. There was not a statistically significant interaction between the use of FM systems and the sequence of testing on SRM scores, F (1,4) = 1.45, $p < 0.3$, indicating that the changes in the SRM between first sequence and second sequence are similar in both conditions, that is with FM and without FM. Therefore, the two runs were averaged.

A repeated-measures analysis of variance was performed to compare the SRM changes in with and without FM conditions. The results revealed that there was a significant effect for FM use indicating that the SRM scores differed at different conditions (with vs. without FM); The interaction graph revealed that the FM systems produced a significant increase in SRM when noise was spatially separated from the speech signal by 90°, [F(1,8) = 117.64, p= 0.0000]. However, there was no significant main effect for the right and left SRM in without FM condition [F(1,8) = 0.56, $p > 0.05$], and with FM condition [F(1,8) =2.52, p=0.15]. There was a large effect size with Cohen’s effect size value of *d* = 0.93. Figure 2 shows the mean 90°+ and 90°– SRMs for both “with FM” and “without FM” conditions.

On average, patients gained 10 dB in SRM when they used the FM systems compared to without FM (see Table 4).

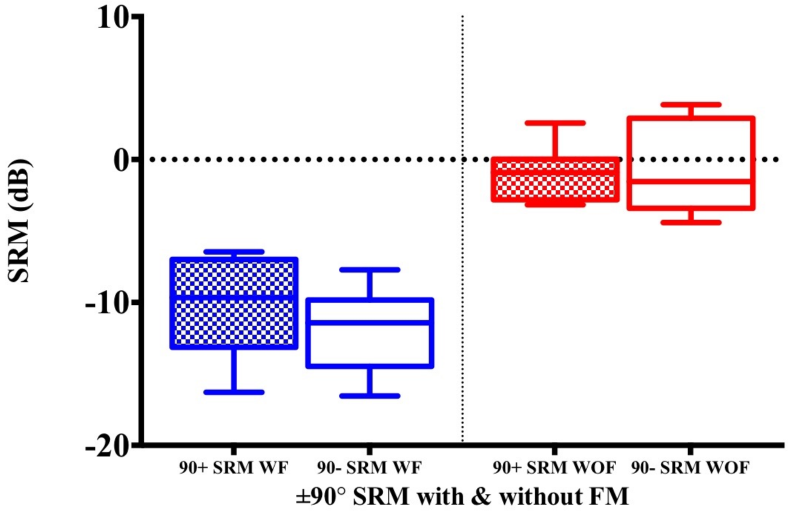


Figure 2: Boxplot of the mean 90°± SRMs of patients in with and without the FM system conditions. SRM, spatial release from masking; WF, with FM; WOF, without FM; +90°, multi-talker babble from the right loud speaker; -90°, multi-talker babble from the left loud speaker.

4. Discussion

Both ischaemic and haemorrhagic strokes may disturb all levels of the auditory pathway and lead to peripheral and central hearing deficits (identified by baseline audiological assessment) or AP deficits (identified by complex tests of AP). However, AP deficits after stroke have not been as extensively investigated as other cortical/subcortical deficits, possibly due to the potentially "invisible" nature of this impairment compared to more obvious symptoms (e.g. dysphasia or motor loss). AP deficits attributable to stroke pathology within auditory pathways are largely neglected by neurologists, and there is a lack of evidence-based treatment for such deficits for the stroke patients with normal hearing thresholds but disordered AP. Our study is novel because it is the first experimental study evaluating the efficacy of FM systems, assessed by speech-in-noise tests in the laboratory, in stroke patients who have difficulty understanding speech in noisy environments due to abnormal auditory processing.

We identified 9 out of 50 (18%) stroke patients who would be eligible for this intervention under stringent selection criteria. All of these patients had normal pure-tone thresholds but had deficits in temporal resolution, perceptual and/or appereceptive spectral processing and in speech-in-noise test performance. Interestingly, our subjects did not have clinically obvious semantic deficits or aphasia. They all reported high levels of auditory disability and auditory-related social and emotional handicap in their everyday life on questionnaires but were not eligible for conventional hearing aids or aphasia targeted treatment. Their presentation would be consistent with an auditory processing disorder, in which their listening difficulties are attributed to impaired processing of the sounds at a pre-semantic level [41]. At present, there is no proven intervention for this population.

All cases significantly improved speech perception in noise with the FM systems, when noise was spatially separated from the speech signal by 90°, by 10 dB SPL on average, compared to unaided listening. The magnitude of the benefit is considerable, as one dB improvement equals approximately a 10% improvement in speech recognition scores at barely audible (threshold) speech levels [42]. Our laboratory findings may thus indicate potentially substantial benefits of FM use in after stroke, for just under 20% of this population.

The observed improvement was more marked for the stroke patients in our study as compared to reports assessing the benefit of FM systems in other neurological populations with auditory processing deficits. Only eight out of ten patients with multiple sclerosis (MS) [22] and four out of six adults with an auditory neuropathy due to Friedreich's ataxia [24] improved. The common denominator between these three different clinical populations is the presence of impaired temporal processing due to the three different types of neural pathology. Friedreich's ataxia is a progressive peripheral de-afferentation type lesion, while MS involves often progressive, widely distributed demyelination in the brain, and it may be that the nature of pathology affects FM outcome. Alternatively, use of more stringent patient selection criteria in our study, in terms of severely impaired speech-in-noise test performance, self-reported speech-in-noise difficulties and non-speech AP deficits, may explain why all our patients showed FM related benefit compared with only 70-80% of patients in the aforementioned studies. Our results need to be replicated in a larger study with longer follow-up that represents real life use of FM devices in these populations more accurately in order to inform clinicians regarding the most appropriate indications of use of these devices.

The observed speech performance improvement in stroke patients may arise from enhanced attention to the speech signal or enhanced neural synchrony and representation of the speech signal in the central auditory nervous system [43]. These influences could be collectively attributed to the improved SNR. Whether the FM technology assists the top-down (cognitive driven) or bottom-up (sensory driven) auditory processing, our study indicates that the benefits gained from the personal FM systems may be a promising intervention to address hearing needs in stroke patients in whom the auditory brain is affected but peripheral hearing is preserved. Furthermore, long-term FM system use is reported to improve anxiety levels in neurologically normal patients with disordered auditory processing [20]. It is noteworthy that our sample consists of adults in the employment-age range. Monzani et al [44] conducted a study to investigate the psychological profile and social behaviour of working adults with mild hearing loss. They reported that this group of patients experience more negative emotional reactions and socio-situational limitations than subjects with no hearing problems. Hence, in view of the high HHIE emotional scores in our patients, effects of FM systems on the emotional wellbeing and quality of life of stroke patients should be investigated.

There is a strong interaction between hearing and cognition during speech processing in challenging conditions, and cognitive factors such as memory and attentional selection of information play a role in comprehension [45]. Cognitive impairment is common three months after stroke, and it is associated with poor long-term outcomes, including survival and disability, up to 4 years after stroke [46]. At the cognitive level, declines in speed of processing, working memory capacity, and the ability to suppress irrelevant information might make it more difficult for the listener to handle multiple streams of information, rapidly switch attention from one talker to another, and comprehend and store information extracted from speech for later recall [47]. Stroke patients with cognitive difficulties may have problems in comprehending spoken language, and the cognitive slowing may reduce the ability of stroke patients to manipulate and integrate the on-going flow of information that is received with high-speed rates in challenging noisy listening conditions. One approach to increase processing demands is to improve the SNR. On the basis of this, one would therefore predict that FM system may even help those with no AP deficits as it could reduce cognitive load and improved perception. Further research could usefully explore the use of FM systems in such patients.

Some limitations are worth noting for our feasibility study; although we found a significant speech-in-noise improvement with FM use in a controlled laboratory environment, these results cannot be extrapolated to indicate benefit in the real acoustic world, which is unpredictable and ever-changing [42]. FM systems hold promise for auditory rehabilitation of stroke patients; however, benefits of FM use in everyday life listening conditions after prolonged use requires further investigation. Prospective studies should evaluate whether the improvement translates into improved quality of life, while other factors such as how the system interacts with patient communication demands and auditory lifestyle should also be considered.

In conclusion, personal FM systems are feasible in stroke patients, and may be of benefit in approximately 18% of this population, who are not eligible for conventional hearing aids. A clinically significant improvement of more than 10 dB in SRM in laboratory tests and a large effect size (d=0.93) indicate that FM systems show promise for the remediation of auditory deficits in a significant proportion of the stroke population.

5. Acknowledgment

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6. Declaration of Interest

None declared.

7. References

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