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Frequency-Following Responses in Sensorineural Hearing Loss: A Systematic Review

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Abstract

Purpose

This systematic review aims to assess the impact of sensorineural hearing loss (SNHL) on various frequency-following response (FFR) parameters.

Methods

Following PRISMA guidelines, a systematic review was conducted using PubMed, Web of Science, and Scopus databases up to January 2023. Studies evaluating FFRs in patients with SNHL and normal hearing controls were included.

Results

Sixteen case-control studies were included, revealing variability in acquisition parameters. In the time domain, patients with SNHL exhibited prolonged latencies. The specific waves that were prolonged differed across studies. There was no consensus regarding wave amplitude in the time domain. In the frequency domain, focusing on studies that elicited FFRs with stimuli of 170 ms or longer, participants with SNHL displayed a significantly smaller fundamental frequency (F_0). Results regarding changes in the temporal fine structure (TFS) were inconsistent.

Conclusion

Patients with SNHL may require more time for processing (speech) stimuli, reflected in prolonged latencies. However, the exact timing of this delay remains unclear. Additionally, when presenting longer stimuli (≥ 170 ms), patients with SNHL show difficulties tracking the F_0 of (speech) stimuli. No definite conclusions could be drawn on changes in wave amplitude in the time domain and the TFS in the frequency domain. Patient characteristics, acquisition parameters, and FFR outcome parameters differed greatly across studies. Future studies should be performed in larger and carefully matched subject groups, using longer stimuli presented at the same intensity in dB HL for both groups, or at a carefully determined maximum comfortable loudness level.

Keywords: Frequency following response, fundamental frequency, sensorineural hearing loss, systematic review

1. Introduction

The Frequency-Following Response, or FFR, is a scalp-recorded electrophysiological response to a complex sound [1, 2]. It is distinguished from other auditory evoked potentials because it mimics the temporal and spectral features of the eliciting auditory stimulus with notable similarity [3, 4] (see Figure 1a and 1b). The FFR arises from multiple generator sources, but is believed to be generated mainly in the auditory midbrain, which is a hub of afferent and efferent activity [2, 5-10].

These features enable the FFR to be used to examine (speech) sound processing at the subcortical level, while also being influenced by processing on cortical level [2, 10]. The FFR is thus influenced by the entire auditory pathway. This pathway is illustrated in figure 1d. This differentiates the FFR from the classical click-elicited Auditory Brainstem Response (ABR), which provides information about the integrity of neural transmission through the auditory nerve up to the inferior colliculus [11]. The FFR helps us understand how complex acoustic information is encoded in the auditory system, how it integrates with other senses, and how both of these processes are influenced by experience [12-14].

The FFR can be characterized in a number of ways, each of which provides distinctive information about sound processing. One way to interpret FFR responses is by examining the timing of response peaks in the time domain waveform (see Figure 1b). In the time domain, latencies of response peaks can be quantified, as well as evaluations of relative timing of peaks within a response or of peaks between two responses (e.g., to the same stimulus presented in quiet and in background noise). Additionally, the phase of individual frequencies within the response can be investigated [1]. For instance, the 40 ms stimulus /da/ evokes seven characteristic response peaks that have been named V, A, C, D, E, F, and O. Waves V, A, C, and O represent the transient component of the response, with V, A, and likely C referred to as the onset component. In contrast, wave O is recognized as the offset component. The sustained component is represented by peaks, D, E, and F [15].

In addition to latency measures obtained in the time domain, it is possible to represent the waveform in the frequency domain, by applying a fast Fourier transformation (see Figure 1c). By this transformation, the encoding strength of individual frequencies in the FFR can be examined [1, 16, 17]. This allows us to study the neural encoding of the temporal envelope and the temporal fine structure (TFS) of the stimulus, which are two acoustic features critical for pitch and speech perception [16, 18]. The temporal envelope is reflected in the fundamental frequency (F_0), which is defined as the lowest frequency of a periodic waveform, and corresponds to the periodicity of the sound, or repetition rate of the sound envelope. F_0 is investigated most effectively when averaging of the alternating stimulus polarities is performed. The harmonics (H_1, H_2, H_3, etc.) are whole-number multiples of the fundamental frequency [1, 16, 18]. Typically, all harmonics present in the stimulus are captured in the FFR, at least up to 1.2-1.3 kHz. In a speech stimulus, certain spectral components, called formants (F_1, F_2, F_3, etc.), are of particular importance because they bring the distinctive acoustic feature of the different phonemes, and are independent of the F_0 of the speech sounds [1, 6]. Subtracting the alternating stimulus polarities enhances spectral components of the FFR and eliminates the FFR envelope, enabling a more effective investigation of the TFS [16].

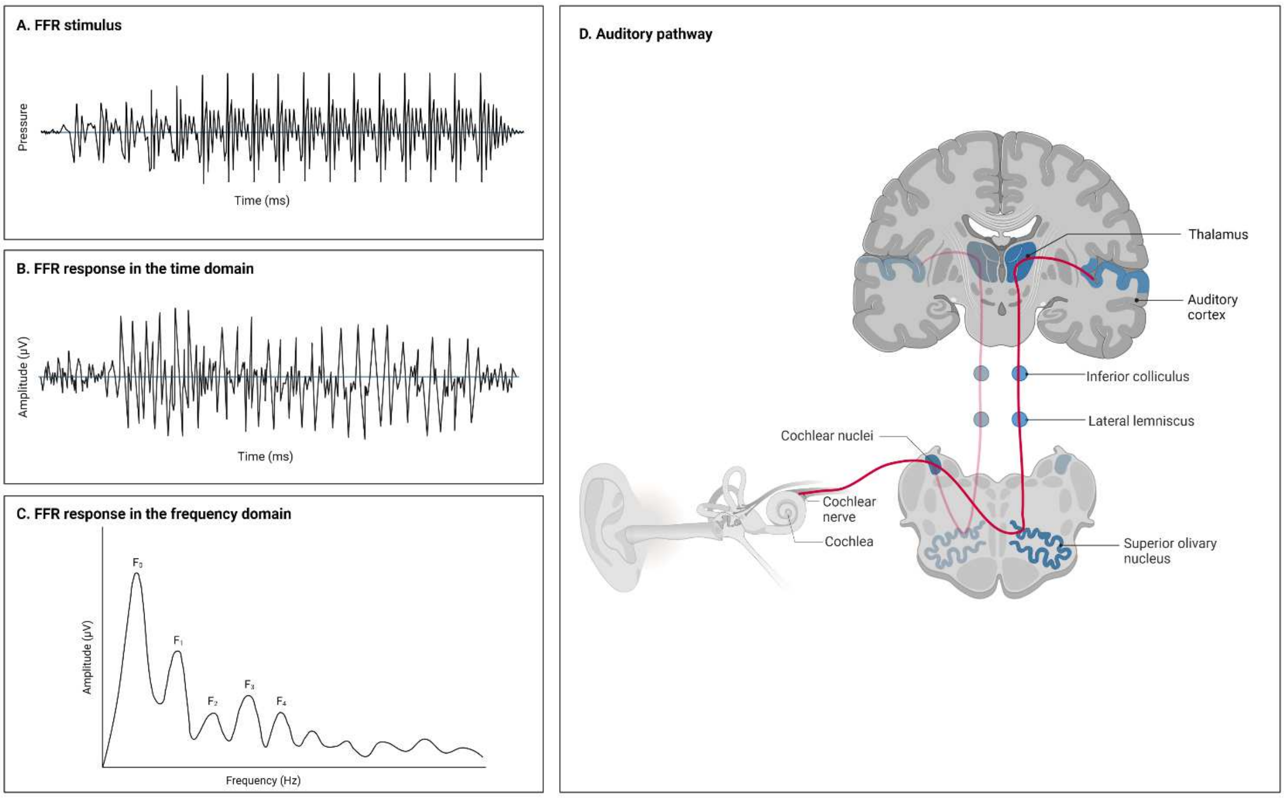


Fig. 1 *(a) Waveform of a typical speech stimulus used to obtain the FFR: a 170 ms /da/ stimulus. (b) FFR response in the time domain. The FFR reflects temporal and spectral features of the eliciting stimulus. (c) By applying a Fast-Fourier transform, the FFR response can be interpreted in the frequency domain. (d) Schematic representation of the auditory pathway. The FFR is generated mainly in the auditory midbrain, but receives contributions by the entire auditory pathway. Created with BioRender.com*

It has been demonstrated that the FFR is affected by various phenomena related to auditory perception and to higher-level language and music processing [19], including pitch discrimination [20], language experience and bilingualism [21-23], and musical training [24-27]. Moreover, several clinical conditions such as dyslexia [28, 29], mild cognitive impairment [30], and autism [31, 32] have been shown to affect the FFR. In addition, it has been suggested that the FFR has potential in the evaluation of cochlear synaptopathy [33, 34] and auditory neuropathy [35].

To date, it remains unclear whether FFRs are also influenced by SNHL. Therefore, the aim of the current systematic review is to assess whether SNHL affects FFRs. A secondary aim is to characterize the optimal parameters to study the FFR in patients with SNHL.

2. Materials and methods

2.1. Protocol registration

The protocol of this study has been registered at the PROSPERO international prospective register of systematic reviews (ID: CRD42022366281) at https://www.crd.york.ac.uk/PROSPERO/. During the design and writing of this study, the Preferred Reporting Items for Systematic Reviews and Meta-analyses Protocols (PRISMA-P) statement [36, 37] was used as a guideline.

2.2. Eligibility criteria

Studies comparing FFRs in patients with SNHL with a normal hearing control group were included. Hearing loss could be unilateral or bilateral, and of any severity. Patients with co-occurrence of significant neurological disease were excluded. Studies investigating FFRs in patients using cochlear implants (CIs) were also excluded. There were no restrictions implemented on age of the patients. The included outcomes were all FFR parameters, both in the time and frequency domains. Regarding study design, we excluded reviews, systematic reviews, and meta-analyses.

2.3. Search strategy

The search strategy was based on the domain-determinant-outcome model [38]. In this model, the domain was defined as patients with SNHL. FFR parameters were the determinants, and the outcome was described as the occurrence of alterations in FFR parameters in patients with hearing loss compared to controls.

The databases that were searched in the scope of this systematic review are PubMed, Web of Science, and Scopus. Search strings were adapted for each of these databases. The reference list of potential sources was screened for additional articles. The search strategy included terms relating to SNHL and FFRs. There were no restrictions on date of publication or language. The date of the last search was October 17th 2023. The search strategies for each of the databases are presented in the Supplementary Information, section A.

2.4. Study selection

Titles and abstracts of the articles retrieved by database searches were screened by two independent authors (LJ and LB). Articles that were included based on the title and abstract and met the eligibility criteria were subsequently subjected to a full-text screening by the same two independent authors. In case of disagreement, this was resolved by a consensus meeting between the two reviewers. If a consensus could not be reached, an extra reviewer (ML) was consulted.

2.5. Data extraction

A standardized form was used for data extraction. The following data were extracted by the two reviewers (LJ and LB): author, year of publication, study design, characteristics of the study population (number, sex, age, hearing level), inclusion and exclusion criteria, study protocol/methodology, outcome measures, and results (values of FFR parameters and standard deviations when available).

Additionally, data regarding acquisition parameters were extracted. This includes the used equipment, stimulus, stimulus duration, number of sweeps, intensity, polarity, presentation rate, window, stimulated ear, and examination conditions.

Because of compelling heterogeneity in both the study population as well as in the acquisition parameters, conducting a meta-analysis was not considered feasible.

In the results section, results of studies that used shorter stimuli of around 40 ms and studies that used longer stimuli of at least 170 ms will also be discussed separately. The reasoning behind this is that longer stimuli allow for better phase locking than shorter stimuli [15, 39], so stimulus duration might affect the results of individual studies.

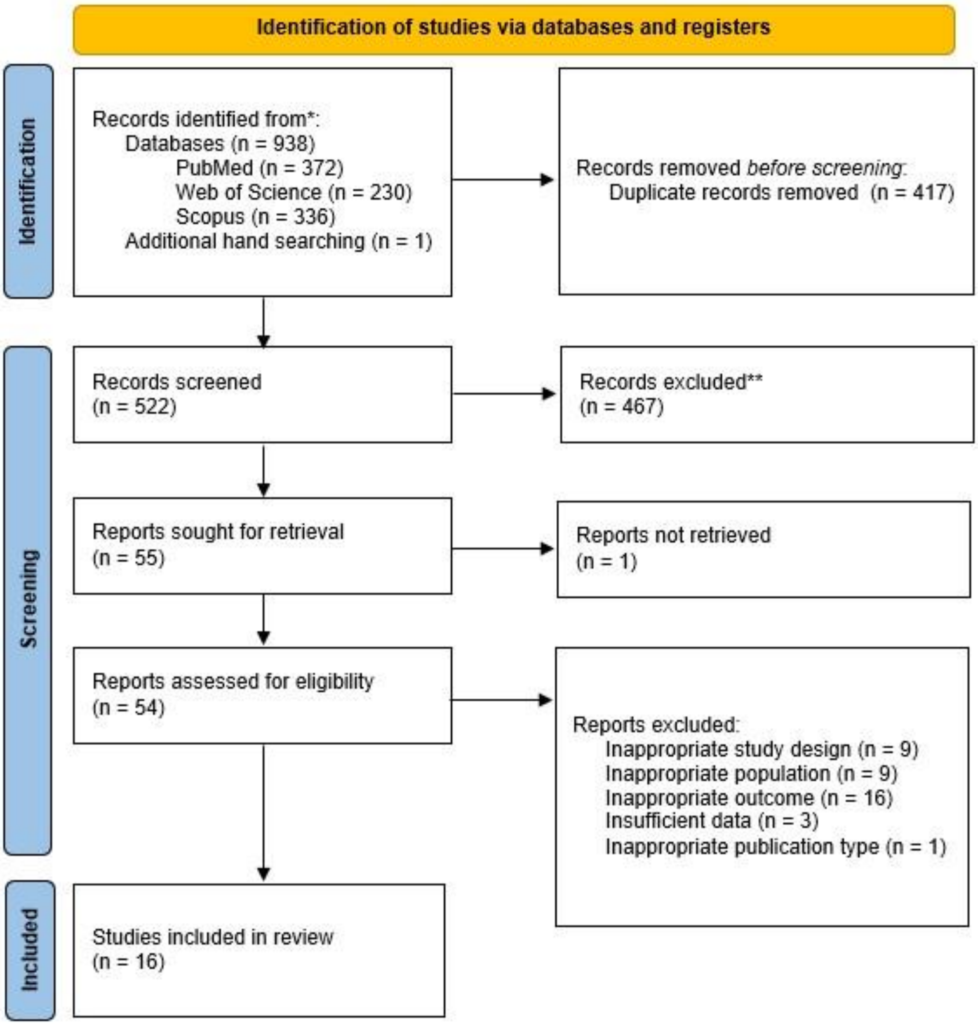
2.6. Quality assessment

Quality assessment was performed using the Newcastle-Ottawa quality assessment scale (NOS) for case-control studies [40]. The NOS uses a star rating system to evaluate the quality in three categories: selection, comparability, and exposure or outcome. Each criterion met is rewarded with a star, with a maximum of nine stars attainable. The awarding of a star signifies that the criterion has a low risk of bias. No definitive cut-off values exist for the NOS, therefore the values described in McPheeters et al. [41] were employed. A score of 7 or higher was defined as good, a score between 5 and 7 as moderate and scores lower than 5 as poor. Two independent reviewers (LJ and LB) conducted the risk of bias assessment, and discrepancies were resolved through discussion.

3. Results

3.1. Study selection

A total of 938 articles were retrieved from the search databases, one paper was retrieved by additional hand searching. After the removal of 417 duplicates, the articles were subjected to title and abstract screening. In this phase, 467 articles were excluded. After full-text screening, 16 papers were included in this systematic review. A detailed overview of the study selection process can be found in the PRISMA flowchart in Figure 2.



*Consider, if feasible to do so, reporting the number of records identified from each database or register searched (rather than the total number across all databases/registers).

**If automation tools were used, indicate how many records were excluded by a human and how many were excluded by automation tools.

Fig. 2 *PRISMA flowchart of the study selection procedure [37].*

3.2. Study characteristics

Sixteen case-control studies comparing FFRs between patients with hearing loss and controls were included (see Tables 1 and 2), of which one had a longitudinal design. The average number of patients with hearing loss enrolled in these studies was 18, ranging from 6 to 40. On average, 19 control participants, ranging from 6 to 45, were included. The mean age of patients with hearing loss was 38.5 years, ranging from 4 to 86 years, and the mean age for controls was 30.5 years, ranging from 4 to 78 years. The proportion of male patients in the hearing loss group was, on average, 54.5% (ranging from 26.7 to 71.4%). In control groups, the proportion of male participants was 39.9% (ranging from 10 to 60%).

The investigated FFR parameters varied across papers. In the time domain, five studies investigated changes in peak latency and amplitude [42-46]. In the frequency domain, F_0 changes were studied by six papers, this being the most investigated FFR parameter [22, 42, 47-50]. Of these studies, four also investigated the TFS [22, 47-49]. Two studies focused on signal-to-noise ratio (SNR) [51, 52], and four papers studied the stimulus-to-response cross-correlation, which was defined as the calculated correlation between the stimulus and neural response [48, 52-54].

For each individual study, a summary of the characteristics of the hearing loss group and control group, and relevant results are presented in the Supplementary Information, section B.

3.3. Quality assessment

The studies that met the inclusion criteria were subjected to a quality assessment. According to the predetermined cutoff scores, eleven studies received a good quality rating. Four studies were rated as moderate quality, and one study was rated with as poor quality according to the Newcastle-Ottawa quality assessment scale (NOS) for case-control studies [40]. An overview of the quality assessment is presented in Table 1. Additional information on the different items that were scored can be found in the Supplementary Information, section C. It is noteworthy that the non-response rate was not described in any of the included studies, which was scored in the eighth criterion of the NOS. Therefore, none of the included studies received a star for this specific criterion.

Reference	Selection				Comparability	Exposure			Total NOS	Quality rating
	1	2	3	4	5	6	7	8		
Abd El-Ghaffar et al., 2018 [55]	★		★	★	★ ★	★	★		7	Good
Akhoun et al., 2008 [51]	★			★		★	★		4	Poor
Ananthakrishnan et al., 2016 [47]	★	★	★	★	★	★	★		7	Good
Anderson et al., 2013 [22]	★	★	★	★	★ ★	★	★		8	Good
Fu et al., 2019 [54]	★	★	★	★	★ ★	★	★		8	Good
Hao et al., 2018 [48]	★	★		★	★ ★	★	★		7	Good
Jalaeia and Zakariab, 2019 [44]	★	★	★	★	★	★	★		7	Good
Ji et al., 2023 [45]	★	★	★	★	★★	★	★		8	Good
Koravand et al., 2017 [42]	★	★	★	★	★ ★	★	★		8	Good
Leite et al., 2018 [46]	★			★	★	★	★		5	Moderate
Molis et al., 2023 [52]	★			★	★★	★	★		6	Moderate
Nada et al., 2016 [43]	★	★	★	★	★	★	★		7	Good
Plyler et al., 2001 [56]	★			★	★	★	★		5	Moderate
Presacco et al., 2019 [53]	★	★	★	★	★	★	★		7	Good
Roque et al., 2019 [49]	★	★	★	★	★	★	★		7	Good
Seol et al., 2020 [50]	★	★	★	★		★	★		6	Moderate

Table 1. Quality assessment, performed using the Newcastle-Ottawa quality assessment scale (NOS) for case-control studies. The NOS uses a star rating system to evaluate the quality in three categories. A study can be awarded a maximum of one star for each numbered item within the selection and exposure categories. A maximum of two stars can be given for comparability. The following eight items (described in detail in the Supplementary Information, section C) were assessed: 1. Case

definition 2. Representativeness of cases 3. Controls selection 4. Definition of controls 5. Comparability of cases and controls 6. Ascertainment of exposure 7. Ascertainment for cases and controls 8. Non-response rate.

3.4. Synthesis of results

3.4.1. Overall results

An overview of the results of the most commonly reported FFR parameters are visually displayed in Table 2. In the following paragraphs, we will discuss the results for each FFR parameter individually.

Reference	**Time domain**		**Frequency domain**			
	Latencies	**Amplitudes**	**F_0**	**TFS**	**SNR**	**S-R correlation**
Akhoun et al., 2008 [51]					↓	
Ananthakrishnan et al., 2016 [47]			↓	↓		
Anderson et al., 2013 [22]			↑	=		
Fu et al., 2019 [54]						↓
Hao et al., 2018 [48]			↓	=		↓
Jalaeia and Zakariab, 2019 [44]	↑ *(waves V, A, and C)*	↓ *(wave A)*				
Ji et al., 2023 [45]	↑ *(waves A, C, E, and O)*	↓ *(wave A)*				
Koravand et al., 2017 [42]	↑ *(waves D and E)*	↑ *(wave O)*	↑ *(RMS of F_0)*			
Leite et al., 2018 [46]	↓ *(wave V at M9)* ↑ *(wave O at M3 and M9)*	↓ *(V-A amplitude at M0 and M3, not at M9)*				
Molis et al., 2023 [52]					↓ *(OHI vs YNH)* = *(OHI vs ONH)*	↓ *(OHI vs YNH)* = *(OHI vs ONH)*

Nada et al., 2016 [43]	↑ *(wave V for /da/ and /ba/, wave A and C in left ear for /da/; wave A and F for left ear for /ba/)*	=				
Presacco et al., 2019 [53]		↓ *(OHI vs YNH)* = *(OHI vs ONH)*				↓ *(OHI vs YNH)* = *(OHI vs ONH)*
Roque et al., 2019 [49]			= *(OHI vs ONH vs YNH)*	↓ *(OHI vs YNH)* = *(OHI vs ONH)*		
Seol et al., 2020 [50]			↓			

↑	Significantly ($p < 0.05$) larger, or longer latency, in SNHL
=	No difference between SNHL and normal hearing controls ($p \geq 0.05$)
↓	Significantly ($p < 0.05$) smaller, or shorter latency, in SNHL
	This FFR component was not reported in this study

Table 2. Visual representation of the results of the most commonly reported FFR parameters across the different included studies. Several FFR parameters that were reported by a small number of the included studies only were not included in this table.

Abbreviations: OHI = older hearing-impaired group, ONH = older normal hearing group, YNH = younger normal hearing group, M0 = initial evaluation, M3 = 3 months after initial evaluation for the control group and after hearing aids adaptation for the SNHL group, M9 = 9 months after initial evaluation for the control group and after hearing aids adaptation for the SNHL group.

3.4.2. Time domain

<u>Latencies</u>

All five studies that investigated latency changes in the time domain reported prolonged latencies of at least one of the response peaks in patients with SNHL [42-46]. Jalaeia and Zakariab [44] found significantly prolonged latencies of the waves V, A, and C ($p < 0.001$, $p < 0.001$, and $p = 0.001$, respectively). Ji et al. [45] reported prolonged latencies of waves A, C, E, and O ($p = 0.007$, $p = 0.042$, p = 0.037, and p < 0.001, respectively). On the other hand, the prolonged latencies in children with SNHL described by Koravand et al. [42] were waves D (p = 0.04) and E (p = 0.05). Nada et al. [43] reported a prolonged wave V in response to both /da/ and /ba/ stimuli (/da/ stimulus: right ear p = 0.031, left ear p = 0.022; /ba/ stimulus: right ear p = 0.041, left ear p = 0.012), as well as for waves A (p = 0.014) and C (p = 0.043) in the left ear only in response to a /da/ stimulus and for waves A (p = 0.005) and F (p = 0.045) in the left ear only in response to a /ba/ stimulus. An exception can be found in the study by Leite et al. [46], where they observed a shorter latency of wave V nine months after hearing aid fitting in the SNHL group compared to the control group at nine months after the initial evaluation (p = 0.007). Additionally, they noted a prolonged latency in wave O for the SNHL group at both the 3-month and 9-month follow-up points (p = 0.007 and p = 0.004, respectively).

It must be noted that Koravand et al. [42], Jalaeia and Zakariab [44], Ji et al. [45], and Leite et al. [46] all elicited FFRs using a 40 ms /da/ stimulus, while Nada et al. [43] used a longer /da/ stimulus with a duration of 206 ms, as well as a 114 ms /ba/ stimulus.

Amplitudes

Regarding amplitude changes in participants with SNHL, there were three studies reporting significantly decreased amplitudes in the time domain in patients with SNHL [44-46]. More specifically, the significantly decreased peak was wave A in both Jalaeia and Zakariab (p < 0.001) [44], and in Ji et al. (p < 0.001) [45]. Leite et al. [46] reported a significantly smaller V-A amplitude at M0 (initial evaluation) (p = 0.04) and M3 (3 months after initial evaluation for the control group and after hearing aids adaptation for the SNHL group) (p = 0.02), but not at M9 (9 months after after initial evaluation for the control group and after hearing aids adaptation for the SNHL group) (p = 0.080). On the contrary, Koravand et al. [42] reported a significantly larger amplitude of wave O in children with SNHL (p = 0.01). There were no significant differences in the other waves. Nada et al. [43] reported no significant difference in any of the waves elicited by both the /da/ and /ba/ stimulus.

Presacco et al. [53] reported significantly smaller amplitudes in both the transition region and the steady-state region in the older adults with SNHL compared to the younger adults with normal hearing ($p = 0.001$ for both the transition and steady-state region), as well as in the older normal hearing group compared to the younger normal hearing adults ($p = 0.048$ for the transition region, $p = 0.014$ for the steady-state region). However, no significant differences were found between the older adults with SNHL and the older normal hearing adults ($p = 0.099$ for the transition region, $p = 0.426$ for the steady-state region).

3.4.3. Frequency domain

Fundamental frequency (F_0)

The most frequently analyzed FFR parameter was the F_0, being investigated in six studies [22, 42, 47-50]. The reported results were inconsistent across these studies. More specifically, three studies reported a significantly smaller F_0 in participants with SNHL [47, 48, 50]. Conversely, Anderson et al. [22] reported a significantly larger F_0 in noise ($p = 0.022$), but not in quiet ($p = 0.304$) for their first condition, in which the unamplified /da/ stimulus was presented to both normal hearing participants and participants with SNHL. For their second condition, in which the unamplified /da/ stimulus was presented to the normal hearing group and an individually amplified /da/ stimulus based on their hearing loss was presented to the SNHL group, the F_0 was significantly larger in quiet and in noise in the SNHL group than in normal hearing controls. Similarly, Koravand et al. [42] reported a significantly larger RMS of F_0 in children with bilateral SNHL ($p = 0.03$) compared to children with normal hearing. Roque et al. [49] reported no significant differences between the three subject groups (older adults with SNHL, young normal hearing adults, and older normal hearing adults) in phase locking factor (PLF) to the temporal envelope ($p = 0.65$). The PLF is a measure for phase coherence for a specific frequency range at each individual point in time during a response.

Temporal fine structure (TFS)

Four studies investigated the TFS. Three of these studies did not report a significant difference in TFS between participants with SNHL and normal hearing participants [22, 47, 49]. In contrast, Ananthakrishnan et al. [47] reported a smaller F1 magnitude for the SNHL group compared to the normal hearing control group across all four tested sound pressure levels (70, 75, 80, and 85 dB SPL). However, when converted to equal sensation level (dB SL), post-hoc analyses indicated only a significant group effect at 60 dB SL, and not at 50 or 55 dB SL.

Signal-to-noise ratio

Akhoun et al. [51] calculated the signal-to-noise ratio as the ratio (in dB) between the root-means square on the whole FFR and the root-means square on the pre-averaging silence. They reported a significantly smaller signal-to-noise ratio in participants with unilateral hearing loss compared to normal hearing controls ($p = 0.001$). Molis et al. [52] calculated the SNR as the ratio of the peak magnitude of the discrete Fourier transform to the response of a ±25 Hz range around the stimulus frequency to the average discrete Fourier transform magnitude of the pre-stimulus baseline in the same ±25 Hz range. Bonferroni-corrected post hoc tests showed a statistically significant smaller SNR in the older adults with SNHL compared to the younger normal hearing group ($p = 0.008$). However, the SNR was not statistically smaller for the older adults with SNHL compared to the older normal hearing adults ($p = 0.620$).

Stimulus-to-response ratio

As for the stimulus-to-response ratio, two out of four studies, more specifically the studies by Hao et al. [48] and Fu et al. [54], reported significantly smaller ratios for the SNHL participants compared to the normal hearing control group ($p = 0.001$ and $p < 0.001$, respectively). In contrast, the study by Presacco et al. [53] did report that the younger normal hearing group had significantly higher stimulus-to-response correlations than either the older normal hearing adults ($p = 0.045$) or the older adults with SNHL ($p = 0.025$). However, there were no significant differences between the older normal hearing adults and the older adults with SNHL ($p = 0.961$). In the study by Molis et al. [52], the stimulus-to-response correlation coefficient (SRCC) was defined as the absolute value of the covariance between the stimulus and response, normalized to a 0-1 scale by dividing by the product of their standard deviations. They reported similar results, being that Bonferroni-corrected post hoc tests revealed that the SRCC was significantly smaller in the older adults with SNHL compared to the younger normal hering adults ($p = 0.003$), but that there was no significant difference for the SRCC when comparing the older adults with SNHL to the older normal hearing adults ($p = 0.216$)

Response to stimulus in quiet and in noise

Five studies acquired FFRs to stimuli presented in quiet and in noise [22, 48, 50, 53, 55]. Three of these compared F_0 component in the quiet condition to the noise condition, and yielded conflicting findings. Seol et al. [50] reported a significantly smaller F_0 in the noise condition compared to the quiet condition for both the SNHL group ($p < 0.0001$) and the control group ($p < 0.0001$). In contrast, Hao et al. [48] did not find a significant difference in F_0 between both conditions for both the SNHL group ($p = 0.124$) and for the normal hearing control group ($p = 0.204$). Abd El-Ghaffar et al. [55] reported a significant decrease of F_0 in the noise condition relative to the quiet condition in subjects with unilateral hearing loss ($p = 0.04$ in study group with left unilateral hearing loss, $p = 0.03$ in study group with right unilateral hearing loss). In the normal hearing control group, no significant difference was found between both conditions ($p = 0.19$ for right ears of control group, $p = 0.13$ for left ears of control group). Other parameters that were compared between both conditions differed between studies, limiting the possibilities for further comparisons.

3.4.4. FFR acquisition parameters

A summary of the equipment and the acquisition parameters used in the included studies is provided in Table 3. The most frequently used stimulus was /da/, being presented in ten of the included studies [22, 42-46, 48, 50, 53, 55]. It is notable that stimulus duration, intensity and presentation rate varied greatly between studies. More specifically, stimulus duration ranged from 40 ms to 543 ms. Seven studies used longer stimuli of 170 ms and more [43, 47-50, 53, 54]. This in contrast with seven of the remaining studies, that presented stimuli of around 40 ms [22, 42, 44-46, 51, 55].

As mentioned in the materials and methods section, we decided to split up results in the frequency domain between studies that used shorter stimuli of around 40 ms and studies that used longer stimuli of at least 170 ms. These results are discussed in the paragraphs below. In the studies by Molis et al. [52] and Plyler et al. [56], durations of the used stimuli fell between these designated durations. However, these studies did not include analyses of F_0 and TFS between, and therefore, they are not addressed in the subsequent sections.

Reference (first author, journal citation, year)	Equipment	Electrode montage (noninverting/inverting/ground)	Stimulus type/stimulus duration	Intensity (dB SPL)	Polarity	Presentation rate (s)	Sampling rate (Hz)	Time window (ms)	Sweeps number for condition	Artifact rejection	Filtering (Hz)	Stimulated ear	Condition	Comments
Abd El-Ghaffar et al., 2018 [55]	Intelligent Hearing Systems	Fz/mastoids/Fpz	/da/, 40.05 ms duration	80	A	10.9/s	NR	0-60	1 x 1024	NR	NR	Monaurally (unaffected ear in study group)	NR	In quiet + with ipsilateral white noise at + 10 and +5 signal to noise ratio (SNR)
Akhoun et al., 2008 [51]	Centor USB	Cz/mastoids/Fpz	/ba/, 60 ms duration	45 dB SL	A	11.1/s	50 kHz	80	3000	NR	80-3200 Hz	Right and left	NR	
Ananthakrishnan et al., 2017 [47]	Intelligent Hearing Systems	1) Fz/mastoid/Fpz 2) Fz/C7/Fpz Recorded simultaneaously and averaged	/u/, 265 ms duration	60-85 in NH listener and 70-95 in HI listener, in 5 dB steps	A	2.76/s	NR	300	4000	NR	50-3000 Hz	Monaurally (Right ear in control group and ear with mild-moderate SNHL in study group)	Relax, were allowed to sleep	
Anderson et al., 2013 [22]	Bio-logic Navigator Pro System (Natus Medical, Inc.)	Cz/earlobes/Fpz	/da/, 40 ms duration	80	A	10.9/s	12 kHz	85.3 (-15.8 - 69.5 ms)	2 x 3000	± 23 µV	100-2000 Hz	Binaurally	Watched muted movie	Quiet and noise condition (noise : + 10 dB SNR)
Fu et al., 2019 [54]	NeuroScan SynAmps2 system (Compumedics Ltd.)	Cz/ipsilateral earlobe/Fpz	Steady tone and three rising FM sweeps, 200 ms duration	75 for NH group, between 15 and 25 for HI group	A	3 FM sweeps: rates of 50, 100 and 200 Hz/s separately	20 kHz	300 (-50 - 250 ms)	3 x 3200 (steady tone + 1 kind of FM sweep)	± 25 µV	30-3000 Hz	Monaurallay (Right ear for NH group, better impaired ear for HL group)	Watched muted movie	
Hao et al., 2018 [48]	Intelligent Hearing Systems	Cz/mastoids/Fpz	/da/, 170 ms duration	85	A	3.89/s	2500	240 (-40 - 200 ms)	1 x 2048	NR	30-3000 Hz	Monaurally (both ears)	Watched	2 conditions: 1) Quiet

													muted movie	2) Noise: continuous white noise ipsilaterally at an SNR of 8 dB
Jalaeia and Zakariab, 2019 [44]	Natus Medical Inc.	Cz/right mastoid (M2)/Fpz	/da/, 40 ms duration	30 dB SL	NR	10.3/s	NR	74.67 ms	2 x 3000	± 23.8 µV	100-2000 Hz	Right ear	Supine position, watching voiceless cartoons	
Ji et al., 2023 [45]	Bio-logic Navigator (Natus Medical, Inc.)	Fpz/mastoid /opposite mastoid	/da/, 40 ms	80	A	10.9/s	NR	85.33 ms	2 x 3000	NR	100-2000 Hz	Inferior ear	Supine or sit on sofa to watch silent cartoons	
Koravand et al., 2017 [42]	Biologic Navigator Pro System (Natus Medical Inc.)	Cz/ipsilateral earlobe/contralateral earlobe	/da/, 40 ms duration	85 in control group, 85-90 in HL group	A	3.1/s	NR	64 ms	1 x 3000, 1 x 2000	20 µV, ≤ 10%	100-1500 Hz	Right ear	Relaxed, closed eyes	
Leite et al., 2018 [46]	Universal Smart Box Jr™ Smart EP, iIntelligent Hearing Systems	Fz/right mastoid (M2)/Fpz	/da/, 40 ms duration	80 dBnNA	A	11.1/s	NR	60 ms	3 x 1000	NR	100-3000 hz	Right ear	Comfortable position	
Molis et al., 2023 [52]	NeuroScan (Compumedics Ltd.)	Cz,C7,left mastoid (M1),Fz/right mastoid (M2)/Fpz	6 tone-glides with varying lide direction (risong/falli	80	A	Varying (interstimulus interval varied)	20 kHz	120 ms (0-40 ms, 40-80 ms, and 80-120 ms)	3000	30 µV	100-3000 Hz	Left ear (unless right ear had a	Reclined position, sleepi	Data were re-referenced for analysis using a vertical montage Cz to

			ng) and extent of frequency change (1/3, 2/3, or 1 octave), 120 ms									lower PTA)	ng was encouraged	C7) and a horizontal montage (M1 to M2)
Nada et al., 2016 [43]	Intelligent Hearing Systems	Fz/mastoids /Fpz	/da/, 206 ms duration /ba/, 114 ms duration	50 dB SL or most comfortable level	A	11.1/s	NR	75 (0-75 ms)	3 x 1024	NR	150-1500 Hz	Monaurally (both ears)	NR	
Plyler et al., 2001 [56]	Tucker-Davis Technologies, System II	Fz/C7/left mastoid	15-step /bɑ/-/dɑ/-/gɑ/ continuum, 100 msec duration	92, 82, and 72	A	5/s	20 kHz	110 ms	2 x 1500	NR	100-3000 Hz	Right ear	NR	
Presacco et al., 2019 [53]	BioSemi ActiABR200 acquisition system (BioSemi B.V.)	Cz/earlobes/ 2 forehead ground common mode sense/driven right leg electrodes	/da/, 170 ms duration	75	A	4/s	16,384 Hz	236 (-47 - 89 ms)	Minimum 2300	± 30 µV	70-2000 Hz	Binaurally	Watched muted movie	In quiet and in the presence of narrating voice presented at 4 noise levels (+3, 0, -3, and -6 dB SNRs)
Roque et al., 2019 [49]	BioSemi ActiABR200 acquisition system (BioSemi B.V.)	Cz/earlobes/ two forehead electrodes	DISH, 483 ms duration DITCH, 543 ms duration	75	A	1.5/s	16,384 Hz	660 ms	3000	± 30 µV	70-2000 Hz	Right ear	NR	
Seol et al., 2020 [50]	NeuroScan SynAmps2 and StIM2 (Compumedics, Inc.)	Cz/earlobes/ Fpz	/da/, 170 ms duration	80 dBA (rms level)	A	NR	20,000 Hz	170 ms	6000	> 20 µV	70-2000 Hz	Binaurally	Watched muted movie	Through loudspeaker 1 m away from participant 0 and +5 dB SNR

Table 3. Summary of the used equipment and acquisition parameters for FFR measurements. Abbreviations: A = alternating, NR = not reported.

3.4.5. Results of studies using a short stimulus (± 40 ms)

Seven of the included studies elicited FFRs by using shorter stimuli of around 40 ms [22, 42, 44-46, 51, 55]. Two of these investigated the F_0. Anderson et al. [22] reported a larger F_0 in the SNHL group in noise, both when presenting the unamplified as well as the individually amplified /da/ stimulus. In quiet, the F_0 was significantly larger in the SNHL group using the individually amplified /da/, but not for the unamplified /da/ stimulus. Similarly, Koravand et al. [42] reported a significantly larger RMS of F_0 in children with SNHL compared to children with normal hearing.

Anderson et al. [22] was the only study that investigated TFS with a shorter stimulus. This study found no differences in TFS between both groups in quiet and noise.

3.4.6. Results of studies using a longer stimulus (≥ 170 ms)

Seven studies used stimuli of 170 ms and longer [43, 47-50, 53, 54]. Four of these studies investigated changes of the F_0 in participants with SNHL. Three out of these four studies reported a significantly smaller amplitude of F_0 in participants with SNHL compared to normal hearing controls [47, 48, 50]. Of these three studies, Ananthakrishnan et al. [47] elicited FFRs by using a 265 ms /u/ stimulus, and Hao et al. [48] and Seol et al. [50] both used a 170 ms /da/ stimulus. The latter two studies reported a significant decrease in F_0 amplitude in noise [48, 50]. In contrast, the fourth study that investigated F_0 changes using a longer stimulus [49], reported no significant differences between the three subject groups in PLF to the temporal envelope.

It must be noted that in the research performed by Ananthakrishnan et al. [47], F_0 was significantly smaller for the SNHL group at all four tested levels in dB SPL (70, 75, 80, and 85 dB SPL). However, when interpreting the FFR data at equal sensation level (dB SL), the F_0 magnitude did not differ between both groups.

Results regarding possible TFS changes in participants with SNHL were inconclusive. Hao et al. [48] reported no significant TFS changes between groups. Similarly, post-hoc analyses performed by

Roque et al. [49] showed no significant differences in PLF to the temporal fine structure between the older adults with SNHL and the two normal hearing groups (older normal hearing adults and younger normal hearing adults). Ananthakrishnan et al. [47] reported smaller F_1 magnitude for the SNHL group at all levels expressed in dB SPL. In contrast, when interpreting this data expressed in dB SL, post-hoc analyses showed that F_1 is only significantly larger in the NH group at 60 dB SL, and not at the other intensities.

3.4.7. Results of studies with similar mean ages in both groups

The mean age in the SNHL groups across studies was 38.5 years, while the mean age in the control groups was 30.5 years. It is noteworthy that some of the included studies carefully matched ages between the two subject groups, while other studies showed big age differences between the groups. Since previous research has shown that age can affect FFRs [57, 58], we decided to look at studies with a mean age gap of less than 10 years separately to investigate whether the studies with bigger age gaps might have affected the results. Eleven of the includes studies reported small mean age gaps between groups [22, 42, 44-46, 48-50, 52, 53, 55]. Two studies did not report mean ages of both groups [43, 56], and were therefore also excluded from this analysis. Detailed results of the most common FFR outcome parameters of these eleven studies with close age gaps are shown in the Supplementary Information, section D.

The overall results, when considering only studies with closer age gaps, resembled the previously described findings obtained when including all studies in the analysis. Anderson et al. [22] and Koravand et al. [42] investigated the F_0 using shorter stimuli, reporting a significantly larger F_0 and RMS of F_0, respectively, in SNHL. As for the three studies using longer stimuli and investigating F_0, Hao et al. [48] and Seol et al. [50] both reported a significantly smaller F_0 in the SNHL group. In contrast, Roque et al. [49] did not report a significant difference in F_0 between the older normal hearing adults and the older adults with SNHL. Four studies included in this section investigated the

FFR in the time domain. All of these studies reported significantly prolonged latencies, with the exact peaks differing across studies. As discussed previously, Leite et al. [46] observed a shorter latency of wave V at nine months (M9) ($p = 0.007$), in addition to a prolonged latency in wave O for the SNHL group at both the 3-month (M3) and 9-month (M9) follow-up points ($p = 0.007$ and $p = 0.004$, respectively).

Regarding amplitude changes, two studies [44, 45] reported a significant decrease in the amplitude of wave A ($p < 0.001$ for both studies). Leite et al. [46] reported a significantly smaller V-A amplitude at initial evaluation (M0) ($p = 0.04$) and at the 3-month follow-up point (M3) ($p = 0.02$), but not at the 9-month follow-up point (M9) ($p = 0.080$). In contrast with these findings, a significantly larger amplitude of wave O in children with SNHL was reported by Koravand et al. ($p = 0.01$). Presacco et al. [53] did not find any significant differences in amplitudes between the older adults with SNHL and the older normal hearing adults, both in the transition region ($p = 0.099$) and in the steady-state region ($p = 0.426$).

4. Discussion

To our knowledge, this is the first paper to systematically review FFR data, available in literature, reported in patients with SNHL compared to normal hearing controls. A meta-analysis was not feasible, due to heterogeneity in the study populations as well as the acquisition parameters.

When interpreting the results of the different studies regarding the FFR in the time domain, there seems to be a tendency towards prolonged latencies of the peaks in SNHL [42-46]. Since peak latencies reflect temporal precision of the synchronous neural activity in response to the stimulus [59], these data could potentially indicate that patients with SNHL require a longer time for processing (speech) stimuli. The exact peaks that occur with prolonged latency differ between studies. Therefore, it remains unclear whether this delay occurs in the onset, transition, steady-state or offset of the response. It must, however, be noted that the study by Jalaeia and Zakariab [44] was the only one of these five studies that presented stimuli in dB SL to both groups. Consequently, we cannot conclude whether this delay reflects a longer processing time, rather than a delay caused by the fact that stimuli were presented at a relatively lower intensity to the SNHL group compared to the control group, since most of the studies did not control stimulus intensity for audibility.

There was no consensus between the six studies that investigated possible amplitude changes of the FFR peaks in the time domain [42-46, 53].

In the frequency domain, the stimulus-to-response ratio was significantly smaller in the SNHL group compared to the normal hearing control group in two studies, reflecting less accuracy of subcortical phase-locking encoding in participants with SNHL [48, 54]. However, Presacco et al. [53] and Molis et al. [52] reported a significantly higher stimulus-to-response ratio in the younger normal hearing group compared to the older adults with SNHL and the older normal hearing adults. However, no significant difference was found when comparing the older adults with SNHL with the older normal hearing adults. The fact that the young normal hearing group had a better representation of the stimulus compared to both older groups and that no differences were found between the two older groups speaks in favor of an age-related degradation of the response.

This finding is in line with the results regarding the signal-to-noise ratio (SNR). For this parameter, one study [51] reported a significantly smaller SNR in participants with unilateral hearing loss compared to normal hearing controls. However, the mean age of the SNHL group was 51 years, while the mean age for the control group was 21 years. As a result, we cannot rule out a possible factor of age-related degradation of the response in this study. Similarly, Molis et al. [52] reported significantly larger SNR in the younger normal hearing group compared to the older normal hearing adults and the older adults with SNHL, with no significant difference between both older groups.

At first glance, the results regarding possible changes of the F_0 and TFS in participants with SNHL seemed rather inconsistent. When focusing on studies that elicited FFRs using longer stimuli with a duration of at least 170 ms, three out of four studies reported significantly smaller amplitudes of F_0 in participants with SNHL compared to normal hearing controls [47, 48, 50]. Since the amplitude of F_0 correlates with the neural encoding of the fundamental frequency of stimuli [1], these results indicate that participants with SNHL show difficulties in tracking the fundamental frequency of (speech) stimuli. In studies that used longer stimuli to elicit FFRs, the findings on TFS were inconclusive, and therefore no definitive conclusions could be made regarding the impact of SNHL on this particular FFR parameter.

4.1.1. Clinical implications

Based on these results, in which we observe that patients with SNHL show a smaller amplitude of F_0, the FFR might be of interest to investigate the effect of hearing aid fitting. BinKhamis et al. [60] elicited FFRs with a 40 ms /da/ presented at 70 dBA in 98 adult hearing aid users. Measurements were performed with and without their hearing aids, in quiet and in noise at +10 dB SNR. the aided situation, all peak latencies were significantly shorter ($p < 0.01$), and amplitudes of peaks V-A, D, and F were significantly larger ($p < 0.01$) compared to the unaided situation , in both quiet and noise. In the frequency domain, F_0 amplitude was significantly larger ($p < 0.01$) in the aided condition compared to the unaided condition in quiet and in noise. These results are to be expected, as hearing aid fitting enhances perception and sensation level. Similarly, FFRs were measured in children with SNHL before and after hearing aid fitting in the study by Easwar et al. [61]. Six phonemic stimuli were presented together as the speech token /suʃi/ at 55, 65, and 75 dB SPL. The use of a hearing aid resulted in significantly larger envelope-following response amplitudes for all stimuli. Direct comparisons between changes in envelope-following response amplitude and sensation level revealed that the degree of change was explained primarily by the change in sensation level provided by the hearing aids. This aligns with a previous study conducted by Easwar et al. in 2015 [62], where it was observed that an increase in stimulus level and the use of hearing aids yielded a significant increase in the number of envelope-following responses detected. Furthermore, at 50 and 65 dB SPL, the use of amplification led to a significant increase in the response amplitude for the majority of stimuli. Karawani et al. [63] performed a longitudinal study in 35 older adults with moderate age-related SNHL. The experimental group used hearing aids during a period of six months, the control group did not use hearing aids during this period. FFRs elicited by the 170 ms speech syllable /ga/, presented at 65 and 80 dB SPL in quiet and in noise (+10 dB SNR), were acquired at initial evaluation and after six months. In the time domain, peak latencies remained stable in the experimental group, but they increased in the control group in the quiet conditions at 65 and 80 dB SPL. The authors suggest that the use of hearing aids may offset the latency delays that may be expected over time in older adults with hearing loss. In the frequency domain, results are inconsistent with the two studies discussed previously. A significant reduction in F_0 amplitude was reported in the experimental group (only in the 65 dB stimulus condition), while no change was observed in controls. They suggest that the use of hearing aids decreases F_0 amplitude over time for conversational level stimuli. One proposed explanation for this finding is that an imbalance between inhibitory and excitatory transmission, which arises with aging, might be "normalizing" as a result of the use of amplification.

Another potential application for the FFR is its use as an objective tool for bimodal benefit, which was investigated in the study by Kessler et al. [64]. FFRs were measured in fourteen unilateral cochlear implant (CI) users who wore a hearing aid in the nonimplanted ear. FFRs were measured in the nonimplanted ear in response to a 170 ms /da/ stimulus. A significant correlation (r = 0.83, $p < 0.001$) between the F_0 amplitude and bimodal benefit for consonant-nucleus-consonant words in quiet was revealed. This relationship remained significant when controlling for four-frequency PTA and accounting for multiple comparisons. There was no significant relationship between the amplitude of F_1 and bimodal benefit for any of the speech recognition tasks. These results indicate that the FFR holds potential as an objective tool that can assess the integrity of the auditory system and help predict bimodal benefit from the nonimplanted ear.

4.1.2. Limitations and directions for future research

Acquisition parameters

A factor to consider when selecting appropriate stimuli for future studies, is the stimulus duration. The stimulus duration differed between the studies, ranging from 40 ms to 543 ms. In our experience and knowledge, longer stimuli allow for better phase locking than shorter stimuli. A /da/ syllable for instance, which is the most frequently used stimulus to investigate FFRs, consists of a transient segment followed by a sustained periodic segment. The transient onset response is similar to the click-elicited ABR. The sustained segment of the stimulus elicits sustained subcortical responses reflecting synchronous neural phase locking, which are reflected in the FFR [15, 39]. Consequently, stimuli need to have a sufficient length to allow this phase locking to occur. Thus, longer stimuli are preferred to investigate phase locking in this population, and for this reason we recommend future studies to select longer stimuli of 170 ms and longer for the acquisition of FFRs.

A key observation from the studies included in this systematic review, is that the majority utilized stimuli presented at the same intensity (in dB SPL) for both the SNHL and the normal hearing control groups, which could have influenced the results discussed in the sections above.

For instance, in the study conducted by Ananthakrishnan et al. [47], the F_0 was significantly smaller for the group with SNHL at all four tested levels in decibels sound pressure level (70, 75, 80, and 85 dB SPL). However, when analyzing the FFR data at equal sensation level (dB SL), no statistically significant difference was observed in F_0 magnitude between the SNHL and control groups. One possible explanation is that the neural representation of the stimulus envelope, as indicated by F_0 magnitude, is comparable for both groups when compared at equal sensation levels. This would suggest that audibility, at least in part, may account for the degraded F_0 representation observed in the SNHL group. Nonetheless, it should be noted that this specific study used a derived measure based on the PTA for each participant within both groups to determine the sensation level associated with each presentation level. Due to inevitable variations in PTA, this computation may result in a wide range of sensation level values within the SNHL group for a given presentation level. Furthermore, the small sample size may reduce statistical power and introduce additional variability, which could lead to insignificant group comparisons. Hence, the equal sensation level comparisons should be interpreted with caution. Nonetheless, these results strengthen the previously discussed argument that presenting stimuli at the same intensity to both the SNHL and normal hearing groups may have affected results. This highlights the importance of our recommendation for future research to control audibility in the experimental design.

Considering the findings of this study, we suggest that the factor of audibility may not have been taken into account when presenting stimuli at same intensity to both groups. Therefore, we strongly recommend future studies to control audibility in the experimental design. One possible approach could involve presenting stimuli at the same intensity in dB SL for both groups. We propose an intensity of around 40-45 dB SL for both groups, as this intensity is high enough to elicit qualitative FFRs, without being uncomfortable for participants [44, 65]. An important consideration regarding this approach, is that matching sensation levels may not be feasible, especially in more severe degrees of SNHL. Alternatively, presenting stimuli at maximum comfortable loudness level could be considered. However, this level should be carefully determined for each participant and stimulus.

This is especially of importance for patients with SNHL, in order to avoid excessively intense stimuli, as the hearing loss may not be uniformly distributed across the spectra. An additional note of attention when using this approach, is that the stimulus may become distorted when presented at higher intensities, affecting FFRs.

Factors related to subject selection

In addition to appropriate stimulus selection, researchers investigating FFR components in SNHL populations must also ensure that their control group is carefully matched to the experimental group. Specifically, matching for age is of particular importance. Failure to properly match these factors may introduce confounding variables that could impact the interpretation of study results. In the current systematic review, the mean age of SNHL participants was 38.5 years, while the mean age for normal hearing control participants was 30.5 years. In previous research by Parthasarathy et al. [57], it was reported that the amplitude of F_0 decreases with age in rats. This decrease of F_0 amplitude with age was confirmed in a human study by Clinard et al. [58], reflecting that neural representation of stimuli becomes weaker as age increases.

To investigate whether this mean difference of 8.0 years between both investigated groups might have affected results, the results of studies with mean age gaps of less than 10 years were discussed separately. When focusing on studies with smaller age gaps only, overall results were not affected.

Nevertheless, a major limitation of the study by Ananthakrishnan et al. [47] is that the mean age of subjects in the SNHL group was 50.66 years, while the mean age of the normal hearing controls was 24.55 years. The observed differences between both groups when presenting stimuli at an equal intensity in dB SPL might therefore be attributed to age degradation rather than hearing loss effects. This highlights the importance of accurate age matching between groups.

It is worth noting that a significant proportion of the studies included in our review lacked precise information on the hearing levels of participants. To address this issue, we suggest that future studies report averaged audiograms or at least pure tone averages for both the experimental and control groups. Clearly, this information is crucial for accurately investigating the impact of (the degree of) SNHL on FFR parameters. Moreover, not all studies clearly specified the etiology of SNHL of the subjects. Because of this lack of information, we were unable to focus on studies that have specifically selected patients with a common etiology.

The study by Goossens et al. [66] could be an example in which subject characteristics were carefully matched and the stimulus were controlled for audibility. A comparative analysis of neural envelope encoding in SNHL subjects and normal hearing controls was performed by measuring auditory steady-state responses (ASSRs) in response to acoustic amplitude modulations. Equal loudness level of stimulus presentation was acquired by setting the stimulus level to 70 dB SPL for the control group, which was rated as comfortably loud by the participant on a graphic rating scale. The sensation level of the 70 dB SPL stimulus equaled to 65 dB SPL. For the SNHL group, every participant was asked to adjust the level of the stimulus until they perceived it as comfortably loud on the graphic rating scale. SNHL and control subjects were divided into narrow age cohorts spanning one decade each. This study's results revealed that, after adjusting for audibility, there was a significant enhancement in neural synchronization within subcortical and cortical auditory regions among young and middle-aged adults with SNHL. However, without accounting for audibility, this enhancement was only observed in the brainstem. This may be attributed to homeostatic mechanisms. It has been demonstrated that the reduced cochlear output in SNHL because of hair cell loss and/or synaptopathy, triggers various mechanisms that induce central gain to sustain an operative degree of neural excitability. Interestingly, older adults with SNHL did not exhibit changes in the degree of neural synchronization relative to normal hearing controls. The reason for this age-related variation is not entirely clear yet. Similar results were found by Farahani et al. [67] in which middle-aged subjects with SNHL showed enhanced ASSR response strength and higher phase-locking. Meanwhile, in older subjects with SNHL, a decreased response strength and less phase-locking was found. The results for the middle-aged groups seem contradictory with our findings that F0 seems to be smaller in SNHL, reflecting difficulty tracking the fundamental frequency of stimuli. This reaffirms the importance of thorough matching based on age between both groups, in order to eliminate effects of age-related degradation.

4.1.3. Conclusion

In conclusion, we report a tendency towards smaller fundamental frequencies in participants with SNHL compared to normal hearing controls. This indicates that patients with SNHL show difficulties in tracking the fundamental frequency of (speech) stimuli. There also seems to be a trend towards prolonged latencies in the time domain, although the specific delayed peaks differ between studies. Results regarding TFS and peak amplitudes in the frequency domain were inconclusive. Participant characteristics, acquisition parameters, and FFR outcome parameters differed greatly across studies. We strongly recommend future studies to use longer stimuli of at least 170 ms to elicit FFRs, as these stimuli allow obtaining more robust and comprehensive information regarding neural phase locking. Finally, future studies should include larger subject groups, and they should control for audibility, for example by presenting stimuli at the same intensity in dB SL for both groups or at a carefully determined maximum comfortable loudness level.

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6. Declaration of Competing Interest

The authors declare no competing interests.

7. CRediT authorship contribution statement

Laura Jacxsens: Conceptualization, Methodology, Formal Analysis, Writing – Original Draft, Writing – Review & Editing, Visualization. **Lana Biot**: Data Curation, Formal Analysis, Writing – Review & Editing. **Carles Escera**: Conceptualization, Supervision, Writing – Review & Editing. **Annick Gilles**: Supervision, Writing – Review & Editing. **Emilie Cardon**: Conceptualization, Writing – Review & Editing. **Vincent Van Rompaey**: Conceptualization, Supervision, Writing – Review & Editing. **Willem**

De Hertogh: Conceptualization, Supervision, Writing – Review & Editing. **Marc Lammers**: Conceptualization, Methodology, Supervision, Writing – Review & Editing.

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