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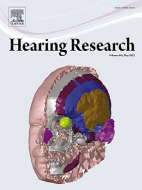

Short review

The frequency-following response to assess the neural representation of spectral speech cues in older adults

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ABSTRACT

Older adults often present difficulties understanding speech that cannot be explained by age-related changes in sound audibility. Psychoacoustic and electrophysiologic studies have linked these suprathreshold difficulties to age-related deficits in the auditory processing of temporal and spectral sound information. These studies suggest the existence of an age-related temporal processing deficit in the central auditory system, but the existence of such deficit in the spectral domain remains understudied. The FFR is an electrophysiological evoked response that assesses the ability of the neural auditory system to reproduce the spectral and temporal patterns of a sound. The main goal of this short review is to investigate if the FFR can identify and measure spectral processing deficits in the elderly compared to younger adults (for both, without hearing loss or competing noise). Furthermore, we want to determine what stimuli and analyses have been used in the literature to assess the neural encoding of spectral cues in older adults. Almost all reviewed articles showed an age-related decline in the auditory processing of spectral acoustic information. Even when using different speech and non-speech stimuli, studies reported an age-related decline at the fundamental frequency, at the first formant, and at other harmonic components using different metrics, such as the response's amplitude, inter-trial phase coherence, signal-to-response correlation, and signal-to-noise ratio. These results suggest that older adults may present age-related spectral processing difficulties, but further FFR studies are needed to clarify the effect of advancing age on the neural encoding of spectral speech cues. Spectral processing research on aging would benefit from using a broader variety of stimuli and from rigorously controlling for hearing thresholds even in the absence of disabling hearing loss. Advances in the understanding of the effect of age on FFR measures of spectral encoding could lead to the development of new clinical tools, with possible applications in the field of hearing aid fitting.

1. Introduction

Speech comprehension often becomes challenging in later stages of life. Older adults tend to report that speech is audible, but that they still have trouble understanding what is being said, particularly in adverse listening situations (Dubno et al., 1984). Even when hearing thresholds are unaffected, older adults often present greater difficulties understanding speech in noise (Frisina and Frisina, 1997; Hopkins and Moore, 2011; Snell and Frisina, 2000) and distorted speech (Gordon-Salant and Fitzgibbons, 1993). Many factors beyond the hearing thresholds have been linked to these age-related speech perception difficulties, such as auditory synaptopathy (Parthasarathy and Kujawa, 2018; Garett et al., 2020) or cognitive declines in working memory, inhibition control and processing speed (Kim et al., 2020; Roque et al., 2019b; Kim and Oh, 2013). Moreover, numerous studies have found that alterations of central auditory processing also contribute to the speech comprehension difficulties of the elderly (for a review, see Humes et al., 2012). These senescent changes in central auditory processing seem to involve a reduction in neural phase locking with age (Leigh-Paffenroth and Fowler, 2006; Anderson et al., 2021). The physiological mechanism underlying this decrease in phase-locked neural activity remains unclear, but some hypotheses based on animal models suggest the involvement of decreased neural inhibition, increased firing variability due to neural noise and increased neural jitter (Anderson et al., 2012).

In recent years, the impact of aging on central auditory processing has been studied using various objective measures, such as conventional auditory brainstem response (ABR;

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Konrad-Martin et al., 2012; Schoof and Rosen, 2016), binaural interaction component ABR (Van Yper et al., 2016), mismatch negativity (Chen et al., 2016; Näätänen et al., 2012), auditory steady-state response (Gaskins et al., 2019; Tlumak et al., 2015), P300 (McCullagh and Shinn, 2018), and magnetoencephalography (Kulasingham et al., 2020). The frequency-following response (FFR) is another of such measure. It consists of a hybrid transient-sustained electrophysiological evoked response that can reliably reproduce the spectral and temporal acoustic features of the speech or non-speech stimuli used (Krizman and Kraus, 2019; Skoe and Kraus, 2010). These measures have shown that age-related decline in the temporal processing contributes to speech understanding difficulties in older adults (for a review, see Anderson and Karawani, 2020). For instance, FFR studies in aging adults have found temporal deficits such as delays during the onset, formant transition and offset of synthesized /da/ syllables (Anderson et al., 2012; Vander Werff and Burns, 2011), as well as weaker encoding of vowel duration cues (Roque et al., 2019b) and silence duration cues (Roque et al., 2019a) in contrasting word pairs.

The auditory processing of temporal acoustic speech cues is critical to achieve an accurate neural representation of speech, but it is not in itself sufficient for successful understanding. Speech also contains important spectral cues such as the fundamental frequency (F0) and its harmonics (Aiken and Picton, 2006; Clinard and Cotter, 2015). These spectral cues are always evolving as a function of time; hence both temporal and spectral processing are connected and needed for speech understanding. Detection of the F0 leads to the perception of voicing, which allows the discrimination of voiced consonants like /z/ from unvoiced consonants like /s/. The neural representation of the F0 gives rise to the perception of pitch (Wagner and Watson, 2010). Changes in pitch over time give rise to pitch contours, which are essential to understand not only sentence types (e.g., question, interrogation, exclamation), but also subtler discursive cues such as the speaker's emotional status (Frick, 1985), syntactic information (Millotte et al., 2007) and irony (Mauchand et al., 2020). Additionally, tonal languages use the suprasegmental pitch contours of syllables to phonologically distinguish between word with otherwise identical segmental structure (Li et al., 2021). Harmonics (or groups of harmonics) that are more amplified than their counterparts are called formants. All the vowels of a language possess a distinctive formant signature that allows us to identify them as different speech sounds. Perceiving change in formants over time (i.e., formant transitions) is also crucial to discriminate some consonants based on their place of articulation (Liberman et al., 1954).

In older adults, the processing of spectral information is far less documented than temporal processing (Clinard et al., 2010), even though there is evidence showing that both temporal and spectral deficits are needed to account for speech understanding difficulties of older adults. For instance, a simulation study concluded that "speech materials needed to be both spectrally and temporally distorted to mimic the effects of age-related differences in auditory processing and hearing loss." (Smith et al., 2012) Both temporal and spectral sound cues are represented in the auditory structures of the nervous system (e.g., cochlear nerve, cochlear nucleus, inferior colliculus) by neurons phase locking to the envelope and the fine structure of the acoustic signal (Clinard and Cotter, 2015; Coffey et al., 2017, 2016; Moore, 2020, 2008a). The FFR offers several ways of assessing the quality of this phase locking (for a review, see Krizman and Kraus, 2019) and can thus be used to gain insightful information on spectral processing of the fundamental frequency, harmonics and formants (Aiken and Picton, 2008).The main goal of this short review is to investigate if the FFR can identify and measure spectral processing deficits in the elderly compared to younger adults (for both, without hearing loss or competing noise). Furthermore, we want to determine what stimuli and analyses have been used in the literature to assess the neural encoding of spectral cues in older adults.

2. FFR assessments of spectral processing

The FFR is particularly well suited to study the way spectral information is represented in the central auditory system because the electrophysiologic response reliably reproduces the spectro-temporal features of the stimuli, plus additional non-linearities not initially present in the stimulus fine structure (Elsisy and Krishnan, 2008). It is then possible to analyze the response waveform as a whole or to examine specific spectral bands by applying a fast Fourier transform (FFT). The FFR encodes the neural phase locking to the envelope and the temporal fine structure in the same waveform. However, it is possible disentangle both components by presenting identical stimuli with opposite polarities: the summation of opposite polarities highlights the FFR to the envelope, while the subtraction of opposite polarities highlights the FFR to the temporal fine structure (Aiken and Picton, 2008). Numerous analyses of the FFR can provide information on the encoding of spectral sound cues (Krizman and Kraus, 2019; Skoe and Kraus, 2010). The **broadband magnitude** measures the overall robustness of the auditory processing. By applying an FFT, it is possible to measure the **spectral amplitudes** indicating the response's strength at specific frequency bands. These frequency bands can be relatively small and centered on spectral components of interest (e.g., F0, harmonics) or larger to include broader spectral information (e.g., formants, higher harmonics). Magnitude can be measured as an absolute amplitude or as a relative amplitude with a signal-to-noise ratio (SNR). The **phase coherence** measures the consistency of the neural phase locking across multiple trials with the same stimuli. Since the FFR replicates the stimulus, it is also possible to measure the **stimulus-to-response correlation** to assess to accuracy of the neural representation of the stimulus. All these analyses can be done on the whole response, or on specific time windows that corresponds specific regions of interest in the signal (formant transition, steady state). FFR studies can obtain valuable information on the neural encoding of spectral information of simpler non-speech stimuli or of more complex speech stimuli (see Table 1 for a summary).

2.1. Non-speech stimuli

Clinard et al. (2010) assessed the effect of age on the auditory processing of pure tones. The authors recorded the FFR in response to 500 ms tone bursts at three frequencies around 500 and 1000 Hz (463, 499, 500, 925, 998, and 1000 Hz) from a group of normal hearing adults ($n = 32$, ages 22–77, thresholds $\leq$ 25 dB HL from 250 to 8000 Hz). Response amplitude and phase coherence were then calculated and modeled with a simple linear regression. Age was found to negatively correlate with both phase coherence and response magnitude around 1000 Hz, but not around 500 Hz. In a follow-up study, Clinard and Cotter (2015) investigated the effect of aging on the neural representation of dynamic rather than static frequencies. The authors recorded FFR of younger adults ($n = 10$, ages 21–24) and older adults ($n = 9$, ages 51–67, thresholds $\leq$ 25 dBHL from 250 to 4000 Hz) in response to 150 ms rising or falling tonal sweeps of different rates (1333, 3999, 6777 Hz/*sec*), respectively starting or ending at 400 Hz. In all conditions, older adults had a less accurate and a weaker representation of these frequency sweeps, as measured by stimulus-to-response correlation and SNR amplitude respectively.

The results from Clinard et al. (2010) in the static 1000 Hz tone conditions are similar to the results of Clinard and Cotter (2015). The former study found that tones with static frequencies around 1000 Hz are less accurately and less strongly repre-

Table 1
Summary of the methodology and findings relevant to spectral processing in the studies forming the main review.

Study	Groups	FFR Stimuli	Audiometric criteria for older adult	FFR spectral results for older participants
Clinard et al., 2010	$n = 32$ (28F), ages 22–77, in condition 1;$n = 28$ (24F), ages 22–77, in condition 2	500-ms TB **Condition 1**: 925, 998, 1000 Hz **Condition 2:** 463, 499, 500 Hz	Tresholds ≤ 25 dBHL from 250 to 8000 Hz	Age is predictive of FFR PC and amplitude around 1000 Hz ($p < 0.05$ or trending towards significance); Age is not predictive of FFR PC or amplitude around 500 Hz; FFR PC or amplitude is not predictive of behavioral results.
Vander Werff and Burns, 2011	**YA:** $n = 19$ (13F); ages 20–26 **OA:** $n = 18$ (17F);ages 61–78	40-ms /da/	PTA from 250 to 8000 Hz ≤ 25 dBHL (mean was 14 dBHL for OA vs 2 dBHL for YA)	No difference in broadband amplitude between groups; Lower amplitudes at three harmonic components (F0, F1, HF), but did not remain significant with HFPTA as a covariate.
Anderson et al., 2012	**YA:** $n = 17$ (13F);ages 18–30 **OA:**$n = 17$ (14F); ages 60–67	170-ms /da/	Thresholds ≤ 25 dBHL from 125 to 8000 Hz, no air-bone gap > 10 dBHL, no interaural asymmetry	Lower broadband amplitude and lower overall response consistency, more significant during the steady-state vocalic region; Lower phase locking in the F0 and in following harmonics.
Clinard and Cotter, 2015	**YA:** $n = 10$ (7F);ages 21–24 **OA:**$n = 9$ (8F); ages 51–67	150-ms frequency sweeps; rise or fall; 1333, 3999, 6667 Hz/sec	Thresholds ≤ 25 dBHL from 250 to 4000 Hz	Lower response SNR and lower stimulus-to-response correlation; Degraded neural representation of dynamic frequencies, even around 400–600 Hz; No effect of sweep direction (rise or fall).
Skoe et al., 2015	**Total:** $n = 586$ (293F);ages 0–73; divided in 12 age groups **OA:** $n = 24$;ages 60–73	40-ms /da/	Thresholds < 20 dBHL from 250 to 4000 Hz	Lower response consistency than younger adults;Lower response amplitude at the low-frequency component of the FFR (i.e., the F0); Main effect of age across all age groups on the response amplitude at the mid- and high-frequency component, showing a decline starting in the childhood.
Mamo et al., 2016	**YA:** $n = 22$ (17F);ages 18–30 **OA:**$n = 22$ (15F);ages 65–80	170-ms /da/	Thresholds ≤ 30 dBHL from 250 to 4000 Hz	Lower response SNR signal-to-noise ratio at the F0 and 2–7 harmonics; No interaction between age and frequency.

The table shows the main articles that were examined to establish which stimuli and audiometric criteria were used in the FFR literature. The results presented in these studies that were specifically relevant to spectral processing are presented in the rightmost column.
Legend: PC: phase coherence, TB: tone bursts, YA: younger adults, OA: older adults, HFPTA: mean high-frequency pure tone average (2000, 4000, 8000 Hz), SNR: signal-to-noise ratio.

sented in the FFR of older adults, while the latter found similar results for rising or falling frequency sweeps over the range of 400 to 1500 Hz Clinard et al. (2010). However, did not find any significant effect of age on the FFR accuracy and strength of static frequencies around 500 Hz. The reason for this difference in the 500 Hz condition compared to the other results from Clinard and collaborators is still unclear. One might first speculate that, since neurons have decreasing phase-locking capacities as frequency increases, the encoding of lower frequencies may be more resilient to the effects of aging than higher frequencies. Secondly, Marmel et al. (2013) note that the neural representation of simpler stimuli such as static tones may benefit more from cochlear place cues, whereas the encoding of more complex stimuli such as frequency sweeps might be more reliant on fine structure cues to be accurate Clinard et al. (2010) also found that the FFR alone was not predictive of behavioral frequency discrimination at 500 or 1000 Hz as measured by a frequency discrimination limen test. However, other studies (e.g., Krishnan et al., 2012; Marmel et al., 2013) found that the FFR was correlated with such behavioral tests of frequency discrimination and were unable to replicate the findings of Clinard et al. (2010) and Marmel et al. (2013) offer multiple hypotheses to explain this conflicting result between studies, such as sample effects (e.g., musical or tonal language experience) or methodological differences (e.g., using iterated ripple noise stimuli instead of pure tones).

In addition to pure tones and frequency modulated tones, other types of non-speech stimuli can be used to evoke FFRs, such as stimuli composed of multiple tones or with amplitude modulations. For instance, Dimitrijevic et al. (2016) employed an amplitude modulated broadband noise carrier with a slowly evolving modulation depth to obtain FFR recordings from young normal hearing adults ($n = 12$, ages 18–28), a first group of older adults ($n = 12$, ages 41–63, pure tone average=30 dBHL) and a second group of even older adults ($n = 12$, ages 67–82, pure tone average=49 dBHL). The study's main finding concerning aging and amplitude modulations was that, as age increases, the auditory system's ability to tell apart different modulation depths decreases, and the neural encoding of amplitude modulations tends to saturate earlier. These findings are relevant because noise can make it harder to detect subtle modulation of the speech envelope, which may contribute to older adults' speech in noise difficulties. Amplitude modulated noise has also been used as a masker for other stimuli. However, Schoof and Rosen (2016) demonstrated that even if the FFR to the speech envelope (obtained by the addition the opposite polarities of a stimulus) decreases with aging, the FFR of older adults were not disproportionately affected by static or amplitude modulated noise compared to younger participants.

2.2. Speech stimuli

Vander Werff and Burns (2011) compared the FFR of older adults ($n = 18$, ages 61–78, mean thresholds ≤ 25 dBHL from 250 to 8000 Hz) to younger adults ($n = 19$, ages 20–26) in response to a 40 ms synthesized /da/ syllable obtained from the Auditory Neuroscience Lab at Northwestern University led by Nina Kraus. This stimulus contains an F0 evolving from 103 to 125 Hz and a formant transition. The study found that the broadband amplitude was similar between groups. In contrast, the narrow band spectral amplitudes were significantly lower in older adults when measured at the F0, the first formants, and higher harmonics. This result suggests that the neural response may be less precise in the spectral domain without being necessarily weaker overall. Furthermore, the authors also specify that these differences disappeared after accounting for group differences in hearing thresholds. These results suggest that the age-related differences in the narrow band spectral amplitudes were likely due to changes in the periphery rather than the brainstem. This study is the only one in this section that accounted for the hearing thresholds of the participants in their results. These findings from Vander Werff and Burns (2011) thus raise the importance of considering participants' hearing thresholds as a covariate when interpreting FFR results.

In a similar study, Anderson et al. (2012) compared older adults ($n = 17$, ages 60–67, thresholds $\leq$ 25 dBHL from 125 to 8000 Hz) to younger adults ($n = 17$, ages 18–30) in response to a longer 170 ms synthesized /da/ that possessed a 120 ms steady-state vocalic region. The study found age-related deficits in the neural representation of specific frequencies, this time using phase coherence as a metric: the phase coherence of the F0 and the following five harmonics were lower. Contrary to Vander Werff and Burns (2011), this frequency specific deficit co-occurred with a broadband amplitude deficit. A later study by Mamo et al. (2016) also found deficits in the neural representation of specific spectral components, but this time by showing a significantly lower SNR amplitude in the F0 and the following six harmonics in older adults ($n = 22$, ages 65–85, thresholds $\leq$ 30 dBHL from 250 to 4000 Hz) compared to younger adults ($n = 22$, ages 18–30) in response to the same 170 ms /da/ stimuli.

One of the largest scale cross-sectional FFR study comes from Skoe et al. (2015) who surveyed the effect of aging on the FFR across the whole lifespan using the short 40 ms /da/ stimuli. Amidst all the participants ($n = 586$, ages 0–73), a group represented older adults ($n = 24$, ages 60–73, thresholds $<$ 20 dBHL from 250 to 4000 Hz). The results showed that the FFR amplitude gradually declines with age after peaking during childhood. In older adults, the most important decrease occurs in the low frequencies (75–175 Hz) which suggests a weaker encoding of the speech F0 with age.

More recent studies have focused less on conventional FFR and have started incorporating more MEG based techniques, which constitute useful tools for fundamental FFR research as they provide insights into the physiological sources of the FFR. Advances in MEG data analysis, such as distributed source modeling, now allow the researcher to more accurately separate and localize the multiple neural generators of complex evoked responses such as the FFR (Coffey et al., 2016). While these studies are mostly concerned with the neurophysiological mechanism underlying the FFR, some studies also investigated age-related changes in the FFR. For example, Ross et al. (2020) found that cortical activity was able to phase lock to the F0 of speech. Interestingly, this cortical contribution to the F0 observed with the MEG-FFR increased with age in amplitude and in phase coherence. In contrast, this was not observed in the conventional EEG-FFR, which is thought to mostly reflect the brainstem's response. This increased cortical contribution with age is not yet fully understood, but points to an age-related cortical involvement beyond early neural processing in the brainstem. Such cortical involvement might be a result of cortical compensation mechanisms shown to appear in older adults when speech is spectrally degraded (Anderson et al., 2020).

3. Discussion

This mini review has shown some evidence in support of age-related deficits in the neural representation of the fundamental frequency (F0). These deficits could play a role in the hearing difficulties of older adults, as strength of pitch encoding has been found to correlate with speech in noise perception in children and older adults (Anderson et al., 2011; 2010). Age-related F0 encoding deficits were observed in the spectral amplitude (Skoe et al., 2015; Vander Werff and Burns, 2011), phase coherence (Anderson et al., 2012; Clinard et al., 2010), signal-to-response correlation and response signal-to-noise ratio (Clinard and Cotter, 2015; Mamo et al., 2016). Using a speech stimulus, similar deficits were also found at specific harmonics (Anderson et al., 2012; Mamo et al., 2016), spectral bands, or formants (Skoe et al., 2015; Vander Werff and Burns, 2011). These findings suggest that aging could be linked to a central auditory processing deficit that affects the encoding of spectral acoustic cues. Whether it results from the same biological process affecting temporal processing remains to be determined. These FFR results may also be linked to behavioral research showing that, even in the absence of elevated hearing thresholds, older adults have a lower sensitivity to the temporal fine structure that can partly account for their speech perception difficulties (Hopkins and Moore, 2011)

3.1. Limitations of the reviewed studies and further research

Most studies using speech evoked FFR to investigate the differences between younger and older adults used a synthesized /da/ stimulus, which presents multiple benefits: the acoustic variables are all controlled, it is designed to elicit strong and reliable neural responses across the lifespan, and it has been extensively studied (Anderson et al., 2012). However, the FFR shines by its versatility and its ability to show the neural encoding of a wide variety of stimuli. In the broader FFR literature, many other synthesized speech stimuli, such as simple /ɑ/ and /u/ vowels (Krishnan, 2002) or other syllables like /ba/ (Akhoun et al., 2008), /da/, and /ga/ (Johnson et al., 2008) have been used to great effect. Of particular interest is a study by Presacco et al. (2015) that compared synthetic /da/ and /a/ stimuli. The author found that older adults presented no significant latency differences between both stimuli, contrary to young adults who had earlier latencies for /da/ than for /a/, as was expected. This result has yet to be fully understood (Anderson and Karawani, 2020), but shows that comparing the FFR to multiple stimuli can produce promising results in the field of aging research. Another possibility for speech FFR is to employ natural speech stimuli, which are more representative of real listening condition at the cost of increased complexity and variability. For example, Jeng et al. (2011) used a Chinese natural speech monosyllable with a rising tone, which was produced by a male speaker, to evoked FFRs. The field of FFR research is known for employing a broad variety of stimuli (for a review, see Skoe and Kraus, 2010), and the study of the aging central auditory system may gain from incorporating some of these stimuli or from creating its own to answer specific research questions.

Clinard and colleagues found no effect of age on the neural representation of 500 Hz static tones (Clinard et al., 2010) but found an age-related decline that persisted around 500 Hz when using rising and falling tones (Clinard and Cotter, 2015). This discrepancy suggests that frequency modulations involve a different processing than static frequencies and are more challenging for older adults. The duration of the stimuli may also have an impact on the results. For example, Vander Werff and Burns (2011) found deficits in specific spectral bands without finding any broadband amplitude deficits using the 40 ms /da/ while Anderson et al. (2012) found that broadband amplitude was lower in older adults using the 170 ms /da/. To better understand the FFR of aging adults, further research could incorporate stimuli with frequency modulation and compare stimuli with different lengths, phonemes, and syllable structures.

A promising FFR technique that has not yet been thoroughly used to investigate the aging processing of the central auditory nervous system is the two-tone evoked FFR

(Pandya and Krishnan, 2004; Lucchetti et al., 2021). Researchers have known for a while that the cochlear non-linearities produced by two-tone stimuli can be encoded in auditory evoked responses (Rickman et al., 1991) and specifically in the FFR (Krishnan, 1999). The two-tone evoked FFR, sometimes called the FFR distortion product, acts a neural counterpart to the acoustic distortion product oto-acoustic emissions (DPOAE) which most strongly encodes the cubic difference tone 2f1-f2, but also the quadratic difference tone f2-f1 (Smalt et al., 2012). If classical DPOAE result from the backpropagation of the cochlear non-linearities, the two-tone FFR results from a neural or pre-neural non-linearities emerging from the multiple stages of auditory processing from the cochlea to the cortex (Elsisy and Krishnan, 2008; Lucchetti et al., 2021). Thus, the FFR can be used to study how non-linearities are encoded in the cochlear nerve, brainstem, and beyond (Bidelman and Bhagat, 2020). However, the present review found that this particular FFR method has yet to be properly employed to study the aging processes of the central auditory processing. This appears to be a considerable hole in the current literature, particularly since non-linearities have been found to be involved in the neural representation of pitch information of unresolved harmonic in complex tones (Smalt et al., 2012) and since the two-tone FFR has been found to be less variable and more identifiable than classical DPOAEs at lower stimulus levels (Elsisy and Krishnan, 2008). It would then be of considerable interest to explore how the neural encoding of non-linearities evolves with aging using FFR evoked by two-tone stimuli.

Robust neural phase locking is required to obtain strong scalp recorded electrophysiological responses. Since phase locking tends to degrade at higher frequencies, the FFR is inherently limited in its upper frequency bound. Although there remain debates regarding the precise upper frequency limit of temporal fine structure coding by neural phase locking (Verschooten et al., 2019), a study by Bidelman and Powers (2018) estimated that phase-locked responses may appear with a sufficient signal-to-noise ratio to appear as amplitude peaks on the FFR (i.e., above the noise floor) up to a maximum around 1500 Hz. Accordingly, most studies in the present review only analyzed low frequency components up to 1000 Hz, with the notable exception of Clinard and Cotter (2015) that used an upper bound of 1500 Hz using simpler non-speech stimuli. It merits to be noted that important spectral speech cues, such as fricatives' spectral identity, lay beyond this upper limit of the FFR. Nonetheless, the low frequency bias of the FFR is particularly interesting in the context of aging, because low frequency thresholds generally remain good even with increasing age, while high frequency thresholds are most likely to decline. As such, low and mid frequency spectral processing deficits could impact speech perception independently of peripheral hearing loss without being visible on the audiogram.

Studies should carefully control for the hearing thresholds of the participants, particularly since hearing thresholds inclusion criteria tend to vary between studies. It would also be valuable for more FFR studies to assess the effect of degree of hearing loss and stimulus intensity on the neural representation of spectral cues in older adults. Older adults often present reduced thresholds in addition to neural encoding deficits, but the interaction between these two age-related deficits is still unclear. It would then be of use to examine if loss of audibility due to sensorineural hearing loss and reduced audibility due to lower stimulus intensity have similar or different impacts on the FFR. Another limitation found in the review was that most studies investigating effects of aging on the FFR had samples composed of predominantly female participants Krizman et al. (2019) found that there exist sex-related differences in the subcortical auditory processing of children and young adults that are reflected in the FFR. For the time being, it is unclear if these sex-related differences remain in the elderly population. Consequently, further studies should control for the sex of their participants and try to recruit samples that are representative of the population of interest. More studies focusing on the relations between aging, sex, and auditory processing are necessary to develop further our understanding of this topic.

In addition to sex and hearing thresholds, other participant characteristics may influence the FFR. Only one of the reviewed studies explicitly controlled for musical experience and bilingualism (Anderson et al., 2012), both of which have been linked to a central auditory processing enhancement in the FFR literature. For instance, research is starting to suggest that lifelong musical expertise may offset some age-related declines in auditory processing at the level of the brainstem (Parbery-Clark et al., 2012; Bidelman and Alain, 2015; Kraus and White-Schwoch, 2017). A study by Skoe et al. (2017) also found that early bilingual adults had an enhanced neural response to the F0 in the FFR compared to monolingual adults, although it remains unclear if such enhancement persists with aging. A review by Grenier et al. (2021) showed that musical training could constitute a rehabilitation tool in older adults without pre-existing musical experience to improve auditory processing, among other potential benefits. Although there is still a lack of strong scientific evidence, this review demonstrates that additional research using objective measures such as the FFR could greatly benefit our understanding of the subject. Therefore, it is advised that researchers consider participant variables such as bilingualism and musical expertise in their methodology and analysis. Further research could also employ the FFR as an objective and versatile tool to investigate the potential protective effects of bilingualism and lifelong musical experience, as well as the effects musical training in auditory rehabilitation.

3.2. Spectral processing and temporal processing

The distinction between spectral processing and temporal processing is not always made clear in the literature. This seems to be rooted in the view that all auditory processing is essentially temporal in nature (Shinn, 2014, 2003) and that, consequently, spectral processing describes merely a subset of temporal processing. Although both types of auditory processing are tightly related, it is misleading to affirm that their relation is hierarchical. Lower frequencies (e.g., $<$1000 Hz) can be encoded in the cochlear nucleus with an enhanced temporal resolution (i.e., stronger phase-locking compared to the auditory nerve) at the cost of added harmonic distortions which deteriorate the spectral representation of the stimuli (Recio-Spinoso, 2012; Lucchetti et al., 2021), whereas higher frequencies produce a weaker phase locking but are encoded with less harmonic distortions in the spectral domain.

Literature on the behavioral assessment of auditory processing use the term *temporal* to refer to “time related aspects of the acoustic signal” (Bellis, 2011, p. 65) rather than to the way information is represented in the central auditory system. Conversely, it seems that the term *temporal processing* is often used in the FFR literature in a very broad manner to describe phase-locking or periodicity deficits, even when the main perceptual correlate is spectral in nature (e.g., pitch). For example, this temporal centric view is explicit in Mamo et al. (2016) where it is said that reduced periodicity is a temporal deficit thought to affect pitch tracking. Although this view is not inaccurate, it is incoherent with the pre-existing literature where *temporal processing* refers to specific abilities such as gap detection, temporal ordering, duration discrimination, forward masking, etc. Some authors seem to be aware of this ambiguity, which they avoid by using terms such as *neural timing, neural synchrony* or *spectro-temporal processing* (Arehart et al., 1997; Grose et al., 2016; Harris and Dubno, 2017; Parbery-Clark et al., 2012) to refer to general deficits in phase locking. Proper distinction between spectral and temporal processes allows researchers to study how they interact and contribute to speech comprehension. This has been done in the past with behavioral studies (Smith et al., 2012) and electrophysiological studies, such as Ceponiene et al. (2009) who compared spectral and temporal processing deficits in children with language impairments using event-related potentials.

3.3. Clinical use of the FFR for older adults

Spectral processing is particularly interesting for hearing aid fitting, since such devices operate mainly in the spectral domain by dynamically amplifying spectral regions associated with different channels (Dreschler, 1992) or even by altering the spectral domain using frequency lowering techniques (Simpson, 2009). Current practices in hearing aid fitting are mostly based on hearing threshold, which may not accurately represent speech perception abilities, particularly in noise (Musiek et al., 2017; Füllgrabe et al., 2014; Humes and Dubno, 2010; Moore et al., 2014). FFR could be used in the fitting process to maximize sound clarity and speech intelligibility by optimizing the neural representation of spectral speech cues without only relying on hearing thresholds (Dajani et al., 2013). This kind of dynamic hearing aid adjustment would be possible since studies have shown that it is possible to collect high quality FFR while the user is wearing their hearing aids by sending stimuli directly to the hearing aids via a wireless connection (Bellier et al., 2015). One hearing aids parameter that could be assessed with the FFR is compression speed, which has been shown to impact spectral contrasts and vowel identification (Moore et al., 2014, 2008b). It has been shown that FFR can be used to predict vowel perception performance in normal hearing adults (Won et al., 2016) and self-reported speech in noise perception in middle-aged or older adults with normal to moderate hearing loss (Anderson et al., 2013). On the other hand, a recent study by BinKhamis et al. (2019) found that the FFR F0 encoding strength was not a good predictor of aided speech-in-noise recognition or self-reported speech understanding with hearing aids. More studies are needed to evaluate if a stronger FFR can lead to increased benefit or satisfaction with hearing aids. Even by optimizing the signal processing to maximize its neural representation, hearing aids would not be able to restore normal hearing. However, this hearing aid fitting approach may be used to individually maximize the auditory neural representation of each patient and thus improve the benefits of amplification.

One of the main concerns of FFR in the clinic is that the evaluation is time consuming Anderson and Kraus (2013) claim that an FFR recording can be done in only 20 min, including electrode placement. This is, of course, still significant, but not necessarily deal breaking in some settings. Recent studies have also shown that the time needed for a reliable FFR recording could drop significantly by using machine-learning techniques (Xie et al., 2019; Yi et al., 2017). Other innovative methods may also reduce the acquisition time needed for some stimuli, such as the generalized primary tone phase variation (gPTPV) method which is able to efficiently disentangle and isolate spectral components in the FFR evoked by a pure tone or multiple tones (Lucchetti et al., 2018). Once the point is reached where the FFR's benefits outweigh its limitations, the FFR could see an increase in clinical applications. More research is still required to achieve this goal, notably to establish if improvement in the FFR with hearing aids translates into better satisfaction and speech understanding in real acoustic environments.

4. Conclusion

Complex sounds such as speech elicit responses in the FFR that can be analyzed in the spectral and the temporal domain. Although there is strong evidence for temporal domain central auditory processing deficit in older adults, less is known about spectral domain deficits. Current results in the FFR literature suggest that neural representation of spectral sound cues such as pitch and formants may decline with age. Further research should aim to clarify the effect of age on spectral processing by using varied stimuli, such as multiple tones, natural speech, and music. Researchers should also consider or control for important participant characteristics, notably their hearing thresholds, sex, linguistic profile and musical experience. Such research could lead to the development of new clinical procedures, such as FFR-based hearing aid fitting.

Declaration of competing interest

None

CRediT authorship contribution statement

L. Chauvette: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **P. Fournier:** Writing – review & editing. **A. Sharp:** Conceptualization, Writing – review & editing.

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