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Effects of temporal fine structure preservation on spatial hearing in bilateral cochlear implant users

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ABSTRACT:
Typically, the coding strategies of cochlear implant audio processors discard acoustic temporal fine structure information (TFS), which may be related to the poor perception of interaural time differences (ITDs) and the resulting reduced spatial hearing capabilities compared to normal-hearing individuals. This study aimed to investigate to what extent bilateral cochlear implant (BiCI) recipients can exploit ITD cues provided by a TFS preserving coding strategy (FS4) in a series of sound field spatial hearing tests. As a baseline, we assessed the sensitivity to ITDs and binaural beats of 12 BiCI subjects with a coding strategy disregarding fine structure (HDCIS) and the FS4 strategy. For 250 Hz pure-tone stimuli but not for broadband noise, the BiCI users had significantly improved ITD discrimination using the FS4 strategy. In the binaural beat detection task and the broadband sound localization, spatial discrimination, and tracking tasks, no significant differences between the two tested coding strategies were observed. These results suggest that ITD sensitivity did not generalize to broadband stimuli or sound field spatial hearing tests, suggesting that it would not be useful for real-world listening.

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I. INTRODUCTION

For patients suffering from bilateral severe to profound hearing loss, the implantation of cochlear implants (CIs) is a state of the art treatment. It is commonly understood that implantation in both ears offers several advantages for the bilateral cochlear implant (BiCI) listeners compared to a unilateral implantation, including improved speech understanding in noise and, most relevant to this study, improved localization of sound sources [van Hoesel and Tyler (2003)]. Compared to unilateral CI listeners, bilateral implantation allows for the perception of spatial hearing cues, such as interaural level differences (ILDs), resulting from the head shadow effect or interaural time differences (ITDs).

However, experiments with BiCI users showed that bilateral implantation is not sufficient to achieve spatial hearing performance at the level of normal-hearing people [e.g., Kerber and Seeber (2012) and Litovsky *et al.* (2009)]. A possible factor could be the coding strategy, as it defines the stimulation patterns of the electrodes inserted into the two cochleae that stimulate the auditory nerve.

The standard coding strategy for CI users can be dated back to 1991 and the introduction of the continuous interleaved sampling (CIS) coding strategy by Wilson *et al.* (1991). In this strategy, bandpass filters split the preamplified signal into frequency bands. The acoustic signal in each frequency band can be decomposed into an envelope function modulating a high-frequency carrier. The rapidly oscillating carrier function makes up the acoustic signal's temporal fine structure (TFS). With the CIS strategy, only the slowly oscillating temporal envelope function is used whereas the TFS function is discarded. The amplitude of the extracted envelope is then compressed and used to modulate brief biphasic pulses at a fixed rate (i.e., 1000 pulses per second or more) at the corresponding electrode. The high definition continuous interleaved sampling (HDCIS) strategy, which was investigated in this study, is a proprietary MED-EL (Innsbruck, Austria) implementation of the CIS coding strategy (Wilson *et al.*, 1991).

However, it is well-known that normal-hearing listeners evaluate ITDs not only in the information of the slowly varying amplitude (envelope) but also in the rapidly oscillating carrier (TFS) of an acoustic signal [e.g., Henning (1974) and Macpherson and Middlebrooks (2002)]. Under normal-hearing conditions, TFS cues are preserved for frequencies up to 1.5 kHz by synchronization of auditory nerve spikes with the carrier's phase [e.g., Verschooten *et al.* (2019)]. Because the CIS strategy stimulates the auditory nerve at

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a fixed rate, no synchronization to the carrier's phase is performed and, as a consequence, TFS cues are not accessible to CI listeners when using a CIS strategy.

To overcome the TFS related limitations with CIS-based coding strategies, TFS coding strategies were developed [e.g., Hochmair *et al.* (2006), Riss *et al.* (2014), and Smith *et al.* (2013)]. Since all participants of the present study were provided with MED-EL CI systems, a focus is put on the MED-EL TFS preserving coding strategy [fine structure preserving sampling (FS4)]. In contrast to the HDCIS strategy, the FS4 strategy does not stimulate all electrodes at fixed rates. With FS4, the timing of the stimulation pulses at the four apical (low-frequency) electrodes follow the zero-crossings of the bandpass outputs and thus try to follow the TFS (Riss *et al.*, 2014). The remaining electrodes (5 to 12) work, similar to the HDCIS strategy, in a constant rate (equal interpulse interval) mode. In all channels and both coding strategies, the pulses' amplitudes are determined by the envelope of the corresponding bandpass filter output. In the case of multiple zero crossings within a certain time frame in different fine structure channels, the channel with the highest amplitude gets the priority and the pulses at the remaining electrodes are either time-shifted or removed (Riss *et al.*, 2014).

Indeed, improved speech and music perception as well as better performance in ITD-based lateralization tasks were observed using TFS preserving strategies [e.g., Churchill *et al.* (2014), Eklöf and Tideholm (2018), Lorens *et al.* (2010), Magnusson (2011), and Müller *et al.* (2012)]. To what extent ITD cues provided by the TFS contribute to the localisation abilities of BiCI subjects remains unclear, although the hypothesis is put forward that the lack of TFS information impedes spatial hearing [e.g., Aronoff *et al.* (2010), Grothe *et al.* (2010), Moua *et al.* (2019), Smith *et al.* (2002), van Dijk *et al.* (2016), Verschuur *et al.* (2005), and Warnecke and Litovsky (2019)].

In this article, we hypothesized that the approach to preserve the TFS with the FS4 coding strategy might enable BiCI listeners to access ITD cues and consequently improve spatial hearing in a number of tasks. Therefore, this study aimed to systematically investigate the effect of a TFS coding strategy on the spatial hearing performance of BiCI users. In previous studies, we already tested the sound source localization, spatial discrimination, and tracking abilities of normal-hearing subjects and BiCI users with an activated pinna-imitating microphone directionality mode and a TFS coding strategy. The results of the normal-hearing subjects were reported in Fischer *et al.* (2020b), and the results of the BiCI were reported in Fischer *et al.* (2021). To enable a direct comparison to the results presented in Fischer *et al.* (2021), in this study we repeated the experiments in the same cohort of CI users, but with a TFS discarding coding strategy, i.e., HDCIS.

We hypothesized that the spatial hearing performance of our subjects is better with the TFS coding strategy than with the HDCIS strategy. For a baseline of basic TFS-related detection abilities, we performed headphone-based tests, including the assessment of ITD-just noticeable differences (JNDs) and the sensitivity to binaural beats (BBs). In addition, the subjective preference of the BiCI users concerning the tested coding strategies was evaluated.

II. STUDY DESIGN

A. Study participants

Our study protocol was approved by the local institutional review board (KEK-BE, No. 2018–00901). Twelve experienced BiCI users and twelve normal-hearing control subjects were included in the study. The CI users and normal-hearing control subjects were the same as in previous studies on spatial hearing abilities performed in Fischer *et al.* (2021) and Fischer *et al.* (2020b). All CI subjects used audio processors with a TFS coding strategy (FS4, Sonnet processor, MED-EL GmbH, Innsbruck, Austria), enabling up to 1000 pulses per second that are timed with the zero-crossings of the signal fine structure Riss *et al.* (2014). The MED-EL implementation of a pinna-imitating microphone directionality (natural mode) was activated for all BiCI users. This pinna-imitating microphone characteristic allows exploiting monaural cues for spatial-hearing tasks due to its direction-dependent frequency transformations [e.g., Blauert (1997) and Fischer *et al.* (2021)]. With the aim of obtaining a homogeneous test group, BiCI users with word recognition scores in quiet (Freiburg monosyllabic word lists) of at least 70% at 60 or 65 dB sound pressure level (SPL) were included. The number of active electrodes between the left and right CI of the subjects was not allowed to differ by more than 1 electrode. An overview of the BiCI study participants is given in Table I. The normal-hearing subjects had an average age of 34 years (range: 24 to 54 years) with air conduction hearing thresholds equal or better than 15 dB hearing level at frequencies between 0.5 and 4 kHz. All participants gave written informed consent before undergoing the study procedure.

B. Study sessions and audio processor fitting

We used a prospective single-blinded repeated-measures design with two study sessions. At least four weeks before the first session, the audio processors of the BiCI users were programmed in a default setting with the FS4 strategy and the fixed microphone directionality mode (natural mode) activated simultaneously. The wind noise reduction feature was disabled, and the automatic gain control (AGC) was set to a compression ratio of 3:1. The sensitivity settings were set to identical values for both processors of each subject. As part of the clinical fitting routine, a subjective loudness balancing of the two audio processors was performed by comparing the loudness sensation of one processor alternately activated, followed by a loudness adjustment when both processors were activated. The stimuli used were speech and noise sounds presented to the subject. In the speech sounds, the audiologist spoke to the CI listener from a frontal position. Then, using percussion instruments, the audiologist produced sounds at a distance

TABLE I. Overview of the study participants. CI = cochlear implant, HL = hearing loss, F = female, M = male. FS4 = fine structure preserving sampling coding strategy. All subjects used a TFS preserving coding strategy (FSP) for at least 1 year before switching to the FS4 strategy. FSP represents the fine structure only on up to the three most apical electrodes (Hochmair *et al.*, 2006), in contrast to FS4, where the TFS is represented up to the four most apical electrodes (Riss *et al.*, 2014).

				Details for left CI / right CI		
Subject	Age (years)	Sex	Etiology	Active electrodes	Experience with CIs (years)	Experience with FS4 (years, months)
CI01	20	M	Congenital/progressive HL[a]	12/12	5/17	0,1/0,1
CI02	67	M	Otosclerosis	10/11	16/15	0,5/0,5
CI03	48	F	Progressive HL	12/12	8/9	7,10/7,10[b]
CI04	62	M	Progressive HL	12/12	6/1	6,3/1,6
CI05	64	F	Congenital/progressive HL[a]	11/11	12/13	8,2/8,2[b]
CI06	66	M	Unknown/progressive HL	12/12	19/17	5,0/5,0
CI07	25	F	Congenital/progressive HL[a]	12/11	17/13	6,7/6,7[b]
CI08	44	M	Meningitis	10/9	12/6	6,7/7,0
CI09	58	F	Progressive HL	10/9	3/6	2,9/5,11
CI10	57	F	Progressive HL	12/12	12/14	7,1/7,8[b]
CI11	62	F	Unknown	12/12	7/1	7,2/0,7
CI12	22	F	Congenital/progressive HL[a]	12/12	4/3	3,10/3,0

[a] Congenital/progressive HL with a profound HL occurring postlingually.

[b] The option to use the FSP strategy by changing the default processor setting was given.

of 10 cm from the ears. The patient was asked to assess whether the volume was perceived identical in both CIs. No matching of single electrodes in pitch or volume was performed.

For the BiCI users, the study included two sessions, with identical tests performed in both sessions but with different coding strategies. In the first session, all subjects performed headphone-based and sound field tests with the default setting they used in everyday life (FS4). Subsequently, the audio processors were re-fitted with a TFS discarding coding strategy, HDCIS. The BiCI subjects exclusively used the new program for at least two weeks before participating in the second study session to repeat the same experiments. After the second session, the participants were free to choose which of the two coding strategies they would like to use as a standard-setting in everyday life. A summary of the fitting parameters is given in the supplementary material.[1]

The frequency allocation for each subject was kept identical for the FS4 and HDCIS coding strategies, ranging from 70 Hz or 100 Hz to 8.5 kHz. When changing the coding strategy, the most comfortable and threshold levels in the four most apical electrodes were readjusted according to the BiCI users' indications. No value judgement concerning the tested coding strategies was made by the audiologist who fitted the CI audio processors. The participants were asked to accustom to a "different" coding strategy without further specifications.

The normal-hearing subjects performed the tests in one session only. For the sound field experiments, the reference data of the normal-hearing subjects are available in Fischer *et al.* (2020b).

III. TEST SETUP

All experiments were performed in a sound-attenuated chamber ($6 \times 4 \times 2\,\mathrm{m}^3$) with an approximate reverberation time of 200 ms for frequencies between 0.25 and 10 kHz. The audio signals for the headphone-based testing were generated using a numerical computing platform (MATLAB R2018a, The Mathworks, Natick, MA, USA) running on a laptop with Linux (Ubuntu 16.04). All audio processing algorithms of the used sound card (HDA Intel PCH with Realtek ALC3235 chip, Intel, CA, USA) were switched off during playback. The signals had a sampling rate of 192 kHz and a bit depth of 24 bits. For the BiCI subjects, the audio signals were directly fed from the laptop's sound card into the audio input of the audio processors using a bilateral audio cable for external sources and adapter (FM battery cover, MED-EL). For the normal-hearing subjects, the acoustic stimuli were presented via in-ear headphones (E1001, Triple-Driver, 1More Inc. San Diego, CA, USA). Before each test, the normal-hearing control group and the BiCI users adjusted the output volume to their most comfortable loudness level.[1] To ensure a proper fit and comparable loudness conditions with the in-ear headphones, individual ear tip sizes were chosen for each participant (Bonnet *et al.*, 2018).

For the sound field experiments, the study participants were seated inside a circular setup consisting of 12 loudspeakers (Control 1 Pro, JBL, Northridge, CA, USA). The setup features wireless controllable robotic carriers with loudspeakers positioned on a circular rail to present acoustic stimuli at arbitrary azimuths during movement or at rest. Movement noise measurements of a loudspeaker at the speed of the sound source tracking test resulted in a sound level of 33 dB SPL at the head of the listener Fischer *et al.* (2020b). During the sound source tracking experiment, the movement noise was obscured by the 65 dB SPL pink noise test stimulus. For minimum audible angles (MAAs), potential noise cues were masked by simultaneous movement of the loudspeakers Fischer *et al.* (2020b). The static sound localization test required no movement of the loudspeakers.

All loudspeakers were covered by an opaque but sound transparent curtain. To avoid head position and gaze-induced bias (Razavi *et al.*, 2007), a trial was not initiated until the interaural axis of the listener was aligned with the loudspeakers at 90° and 270° azimuth. In addition, subjects were instructed beforehand to direct their gaze forward (0°) and informed that gaze and head position would be monitored during the trial and should remain constantly frontally aligned. During the study, no test needed to be repeated or aborted due to head or eye position.

The loudspeaker setup is shown in Fig. 1. For a detailed description of the measurement setup, please refer to Fischer *et al.* (2020b). A video of a sound source tracking experiment is provided as a multimedia file Mm. 1.

Mm. 1. Video showing a sound source tracking experiment with robot controlled loudspeaker, gaze and head monitoring, and touchpad feedback. Sound tracking abilities were tested with a moving loudspeaker (7.4°/s) continuously playing a pink noise stimulus with 65 dB SPL. The participants were instructed to follow the stimulus using the touchpad dialing interface. File of type “mp4” (12.0 MB).

IV. TEST PROCEDURES

The study participants performed five experiments during the test sessions: (1) measurement of ITD-JNDs with pure-tones and pink noise signals (headphone-based tests), (2) detection of BBs (headphone-based test), (3) static sound source localization, (4) MAA assessment, and (5) dynamic sound source tracking. To ensure that the experiments’ tasks were correctly understood and performed by the subjects, a training phase took place at the beginning of each test which is explained in more detail in the respective method descriptions of the tests. If desired by the participants, short breaks were taken between the tests. The order of experiments was counter-balanced to minimize training and fatigue effects. In the study by Fischer *et al.* (2021), the sound-field tasks [(3), (4), and (5)] were performed by the same test group of CI users as in the present study, but with an omnidirectional microphone setting.

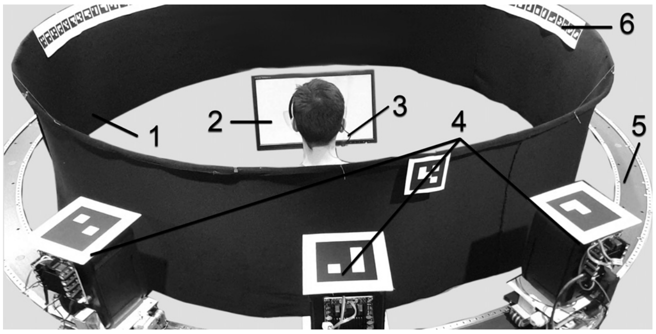


FIG. 1. Robotic measurement setup during minimum audible angle (MAA) assessment at 180° azimuth. The setup consists of the following components: Sound-transparent curtain (1), touch screen with graphical user interface (2), eye-tracking glasses (3), wireless controllable audio robots with optical tracking markers (4), low noise rail (5), and azimuth reference markers (6).

A. Detection of interaural time differences

To assess the ITD-JNDs, two consecutive stimuli were used. The first signal was a diotic reference stimulus without ITDs. After an intra-stimulus interval of 1 s, a second stimulus was presented containing a headphone-based ITD and the participants were asked to indicate to which side the second signal was lateralized. Playing a stimulus with zero-ITD followed by a stimulus containing a non-zero ITD was intended to provide conditions analogous to the MAA test procedure performed in the sound field. A whole-waveform ITD was applied, ensuring that onset and ongoing cues were present.

The JNDs were measured for three different stimulus types with 500 ms duration: (i) 250 Hz sinusoids with 10 ms rise and decay time (Hanning window), (ii) 250 Hz sinusoids with 100 ms rise and decay time, and (iii) pink noise stimuli with 10 ms rise and decay time. The 250 Hz pure-tones were used because normal-hearing listeners evaluate ITDs of the TFS to lateralize low-frequency tones [e.g., Bernstein and Trahiotis (1985), Henning (1980), and Henning and Ashton (1981)]. The rise and decay time of 100 ms was used to facilitate the use of ongoing ITDs instead of ITDs in the onset/offset of the stimulus [e.g., Laback *et al.* (2015)]. For the BiCI users, the 250 Hz corresponds approximately to the centre frequency of the bandpass for the second most apical electrode, which is a TFS-sensitive electrode in the FS4 strategy. The pink noise stimuli were used to link the ITD-JNDs measurements with the spatial hearing experiments performed in the sound field.

To familiarize the subjects with the test, a demonstration of a pink noise stimulus was given with ILD of 12 dB and ITD of 1 ms with feedback during the training. The tests also started with the pink noise broadband stimuli. Broadband stimuli are considered to provide easier conditions than pure-tones to detect ITDs in normal-hearing listeners (Klumpp and Eady, 1956). Subsequently, the pure-tone stimuli were tested, randomly starting with the 10 or 100 ms rise time conditions. No feedback was given to the subjects during the measurements. A two-alternative forced-choice procedure with a 2 down 1 up rule was used to estimate the logistic psychometric function as defined in Shen *et al.* (2015),

$$p_{logistic} = \gamma + \frac{1-\gamma-\lambda}{1+e^{-\beta(x-\alpha)}}, \qquad (1)$$

where x denotes the ITD, α is a threshold parameter that indicates the centre of the function’s dynamic range, β is the slope, γ is the lower bound of the function (fixed value, in our case $\gamma = 0.5$), and λ is the lapse rate (fixed value determined in pilot tests with $\lambda = 0.03$) (Shen *et al.*, 2015). The parameters α and β were estimated in 35 steps with an adaptive ITD step size. The number of steps was chosen as a result of pilot tests before the study. A flat prior probability distribution for α and β was chosen. The step size for upcoming trials was computed using the updated maximum-likelihood (UML) method based on the stimuli and responses from the previous trials (Shen and Richards, 2012).

We chose the 2 down 1 up rule because it is extensively used in psychophysical research (Leek, 2001). Since no staircase procedure was applied, but an UML procedure that estimates a complete psychometric function (Shen and Richards, 2012), the rate of convergence for the psychometric function's parameters is not significantly affected by the 2 down 1 up rule (Shen *et al.*, 2015).

The starting ITD for all subjects was 700 μs. For BiCIs users the upcoming ITDs ranged between 5 and T/2 $= 2000\,\mu$s, where T defines the period of an oscillation and corresponds to 4 ms for 250 Hz sinusoids. The maximum of $\mathrm{T}/2 = 2000\,\mu$s was chosen because in BiCI users natural occurring ITDs of T/3 [see Fig. 1 in Sayers (1964)], often do not lead to full lateralization (Anderson *et al.*, 2019; Baumgärtel *et al.*, 2017). A further increase in the ITD was not implemented because for 250 Hz sinusoids $\mathrm{T} = 4$ ms and an ITD greater than T/2 would lead to confusion of interaural phase likely leading to a perceived lateralization closer to the center of the head. For normal-hearing listeners, the tested ITDs were in the range of 5–700 μs, which corresponds to an ITD induced by a human head at full lateralization (Blauert, 1997).

The ITD-JND was defined as the 80%-correct threshold of the estimated psychometric function, as also applied in Häusler *et al.* (1983), McFadden and Pasanen (1976), and Senn *et al.* (2005). For the BiCI users, the chance level of the procedure was found to be at $1960\,\mu\mathrm{s} \pm 153\,\mu\mathrm{s}$ (normal hearing listeners: $693\,\mu\mathrm{s} \pm 50\,\mu\mathrm{s}$) (see Sec. IV G). The graphical user interface of the test is shown in the supplementary material.[1]

B. Detection of binaural beats

BBs refer to a beating auditory illusion that occurs when two pure tones with slightly different frequencies are presented via headphones or the direct audio input of the CI audio processor. In contrast to the beating caused by physical interference phenomena (monaural beating), BBs are the result of central auditory integration processes (Oster, 1973) and therefore a favourable indicator for binaural integration. To test BB sensitivity, we asked the subjects to listen to three stimuli presented in a randomized order and indicate the stimulus causing a BB (three-alternative-forced-choice procedure). Two of the three stimuli consisted of diotic pure-tones with frequencies of $\mathrm{F_{BB}} - \Delta\mathrm{F}$ or $\mathrm{F_{BB}} + \Delta\mathrm{F}$. A third dichotic stimulus with a frequency of $\mathrm{F_{BB}}$ in one ear and $\mathrm{F_{BB}} \pm \Delta\mathrm{F}$ in the other ear was used as BB stimulus. The BB stimulus produced signals with ITDs periodically varying across the period of ΔF.

Three different stimulus conditions were used for BB testing, each tested with eight repetitions. The first had an $\mathrm{F_{BB}}$ of 135 Hz and ΔF of 3 Hz. This BB condition was chosen, since ITD sensitivity of BiCI subjects is reported to deteriorate above 200 pulses per second [e.g., van Hoesel (2007) and van Hoesel and Clark (1997)]. The second condition had an $\mathrm{F_{BB}}$ of 250 Hz and ΔF of 4 Hz, where the BB-frequency corresponded to the ITD-JND experiment.

The third stimulus type had a frequency of 500 Hz ($\Delta\mathrm{F} = 10$ Hz), which is the frequency reported to be most sensitive to BBs for normal-hearing listeners [e.g., Licklider *et al.* (1950) and Perrott and Nelson (1969)]. The stimuli were Hanning-windowed with rise/fall times of 100 ms.

Before testing the sensitivity to BBs, and to make sure that the subjects are aware of the pulsating signal pattern to be detected, monaural beats (i.e., $\mathrm{F_{BB}}$ and $\mathrm{F_{BB}}+\Delta\mathrm{F}$) were mixed and presented diotically. Monaural beats are easily perceptible due to intensity oscillations. During the training with the monaural beats, feedback was provided to the subjects. Getting accustomed to the beat rate using monaural beats, can help to perceive BBs [e.g., Grose *et al.* (2012) and Oster (1973)]. The participants were allowed to listen to the stimuli for as long and as often as necessary.

The direction of the frequency difference ($\mathrm{F_{BB}}+\Delta\mathrm{F}$ versus $\mathrm{F_{BB}} - \Delta\mathrm{F}$) for the BB stimulus was randomly selected. The BB sensitivity was defined as the detection rate (true positive rate). Since the task was a three-alternative forced-choice procedure, the chance level for the detection rate was 33%. The supplementary material shows the graphical user interface used for testing.[1]

C. Static sound source localization

Sound localization was assessed in a static setting with 12 loudspeakers arranged in a full horizontal circle, resulting in a spacing of 30° between the speakers. We chose pink noise as stimulus type for all sound field experiments, as it approximates the speech spectrum (Voss and Clarke, 1975). In addition, pink noise was also used in a previous study testing the localization ability of BiCI users with an omnidirectional microphone directivity and the FS4 coding strategy Fischer *et al.* (2021). Three stimuli were presented in a randomized sequence from each loudspeaker with roving levels at 60, 65, and 70 dB SPL, for a total of 36 stimuli per test (Wimmer *et al.*, 2017). Level roving was applied to avoid the use of monaural intensity cues. The stimulus duration was relatively short (200 ms with 10 ms rise and decay time) to avoid the influence of head movement (Blauert, 1997).

The participants were instructed that stimuli can be presented from any azimuth. After each stimulus, the subjects indicated the location of the stimulus via a graphical user interface with a dial (1° resolution) and a login button. Consecutive stimuli were presented 2 s after the login button was pressed. Before the test started, the participants completed training on the task until they confirmed that they understood the test procedure. The absolute localization accuracy was determined by the root mean square error ($\mathrm{RMSE_{LOC}}$, in degree angle) for all stimuli ($\mathrm{N} = 36$) [e.g., Hartmann and Rakerd (1989)]. To evaluate the influence of front-back confusions (FBCs) on the localization performance, we used the FBC Rate, which is defined as the proportion of responses crossing the interaural axis with respect to the stimulus position [e.g., Carlile *et al.* (1997)] and the FBC score which refines the FBC rate by weighting the abovementioned responses deviation from the corresponding position on the cone of confusion (Fischer *et al.*, 2020a). The interaural axis is defined by a straight line passing through the left ear (270° azimuth) and the right ear (90° azimuth). A detailed description of the static sound source localization test procedure can be found in Fischer *et al.* (2020b).

D. Minimum audible angle

The smallest angular difference between the sound sources of two successive tone pulses that can be reliably detected defines the MAA (Mills, 1958). To determine the MAA, two tones were played; one of them was shifted either to the right or the left regarding the first tone, which stayed at the reference position. The MAA was estimated for eight reference directions in the horizontal plane, i.e., at 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°. Pink noise double bursts with 200 ms length and an intra-stimulus interval of 1 s at 65 dB SPL were used as test stimuli. To determine the psychometric function [see Eq. (1), with the variable x denoting the angular displacement between both stimuli] for the sound source discrimination task for each of the reference directions, 24 steps with an adaptive size determined by an UML estimation (Shen *et al.*, 2015) with a 2-down 1-up rule were used. The total number of 24 step sizes was chosen based on pilot tests to find a compromise between measurement time and accuracy of the psychometric function's parameters. The starting step size was set to 15°, with the fixed parameters set to $\lambda = 0.03$ (lapse rate) and $\gamma = 0.5$ (lower bound for two-alternative forced-choice procedure). A uniform prior distribution was chosen for the α and β parameters. With the same reasoning as in the ITD-JND task, the MAA was defined as the 80%-correct threshold of the estimated psychometric function. Monte Carlo analysis resulted in a chance level of $83° \pm 15°$ for the applied procedure (see Sec. IV G). Before the test started, the participants trained the MAA task until they confirmed that they understood the test procedure. The training measurement position was at 315° with a starting distance between the two successively played broadband noises of 45°. No feedback was provided during or after testing. Further details regarding our MAA measurement procedure can be found in Fischer *et al.* (2020b).

E. Sound source tracking

Sound tracking abilities were tested with a moving loudspeaker continuously playing a pink noise stimulus with 65 dB SPL. A circular trajectory with 32 changes in direction of movement ("alternating trajectory") was used. A "change in direction of movement" refers to a reversal of the direction of movement of the loudspeaker in either direction Fischer *et al.* (2020b). The participants were instructed to follow the stimulus using the touchpad dialing interface, which was also used in the static sound localization test. The test duration was 4 min 40 s, and the angular velocity of the moving stimulus was 7.4°/s following the observations of Kourosh and Perrott (1990), who observed particularly good auditory resolution of sound source motion for angular velocities in this range. The subjects were seated in the centre of the circularly moving loudspeaker. Before the test, a training trial covering a total range of 450° in azimuth (61 s stimulus duration) with a change of the movement direction at 45° was performed. During the training trial, feedback of the realtime loudspeaker position was indicated on the touchpad dialing interface. The root mean square error between the actual position and the position indicated by the subjects was used to quantify the tracking error (RMSE_ϑ, in degree angle). Also, the proportion of the correctly indicated movement directions (in percentage) and the offset between the perceived velocity and the actual stimulus velocity was determined (RMSE_ω, in degree angle per second).

Further details and animations of the test procedure are available in Fischer *et al.* (2020b) and Fischer *et al.* (2021).

F. Subjective evaluation

The German version of the Speech, Spatial and Qualities of Hearing Scale (SSQ) questionnaire was used to measure the influence of the tested coding strategies on the hearing ability in various environmental conditions of everyday life (Gatehouse and Noble, 2004). Each question of the SSQ can be answered in the range from 0 ("not at all") to 10 ("perfectly") or with "not applicable." High values of the SSQ reflect a subjectively high hearing quality. The questionnaires were handed out to the BiCI users after the default audio processor fitting session and after completion of the first study session. Therefore, the questionnaire covered an observation period of at least two weeks. Normal-hearing listeners filled in the questionnaire before the single study session.

G. Statistical analysis

The main hypothesis of this article was that a TFS coding strategy improves ITD perception and thus spatial hearing as well as the subjective hearing quality of BiCI users. To compare the outcome measures of the tested coding strategies (FS4 versus HDCIS), a two-sided Wilcoxon signed-rank test was used. The decision to use a non-parametric test is justified by the small number of samples and the fact that no normal distribution can be assumed [e.g., Bridge and Sawilowsky (1999) and Nahm (2016)]. The group-level performance was summarized with descriptive statistics. To determine if the BB performances significantly exceed the level of chance rating, a one-sided binomial test was used. The FBC rates and BB detection rates measured with the HDCIS and the FS4 strategy were converted to counts and compared to each other using a Chi-Square test of association. For correlation analysis, we computed the Pearson correlation coefficients between subject characteristics (i.e., word recognition scores, number of active electrodes, stimulation rates, SSQ scores, most comfortable levels, CI experience, and experience with TFS coding strategies) and the outcome measures of our experiments. The significance level was chosen with type I error rate = 0.05. To account for multiple comparisons, the Bonferroni method was applied.

The chance levels of the ITD-JND and MAA tasks were estimated with 50 000 Monte Carlo simulations per task (Metropolis and Ulam, 1949). The tests' chance level reflects the arithmetic mean of the test results of 50 000 simulated participants who chose their answers purely at random and statistically independently of each other. An ITD-JND or MAA below chance level indicates that the participant was not responding randomly across the ITDs and loudspeakers used to present sounds. In the case of the ITD-JND task, the result of one Monte Carlo simulation corresponds to the determined ITD-JND after 35 steps. For each of the 50 000 simulations, the 35 pseudo-patient responses ($N = 35$ steps) were previously generated using the MATLAB function randi([0,1],N,1). The function randi creates N pseudorandom, uniformly distributed scalar integers, either 0 or 1. For the MAA task, the same as with the ITD-JND task applies, but with $N = 24$ steps as defined in our test protocol (see Sec. IV D). The N values were successively passed as input to the uml.update function Shen *et al.* (2015), as with actual patient responses. For each of the 50 000 simulations, a new UML object or psychometric function was initialized (Shen *et al.*, 2015). The parameters α, β, γ, and λ as well as the possible response range of the psychometric function, correspond to the values described in Sec. IV A (ITD) and Sec. IV D (MAA) for the respective test condition. All statistical calculations were performed with MATLAB (version R2018a, The MathWorks Inc., USA).

V. RESULTS

A. Detection of interaural time differences

The JNDs for the test conditions are shown in Figs. 2 and 3. For the 250 Hz frequency and 10 ms rise and decay times stimulus, we observed a statistically significant improvement of the ITD-JNDs when using the FS4 strategy. With the HDCIS coding strategy, higher JNDs of 1348 μs [$SD = 545\,\mu$s, interquartile range (IQR) = 846–1811 μs] were measured compared to the JNDs with the FS4 strategy (1030 μs, SD = 753 μs, IQR = 372–1914 μs, $p = 0.02$, $W = 7$, $N = 12$).

For comparison, normal-hearing listeners achieved mean JNDs of 84 μs (SD = 76 μs, IQR = 37–116 μs) in our experiment. Using the FS4 strategy, five of the 12 BiCI subjects had a sensitivity substantially below the physiological threshold of 700 μs compared to 2 out of the 12 subjects using the HDCIS strategy. The physiological JND-ITD limit of T/2 was exceeded for 1 subject with the HDCIS strategy and 2 subjects with the FS4 strategy.

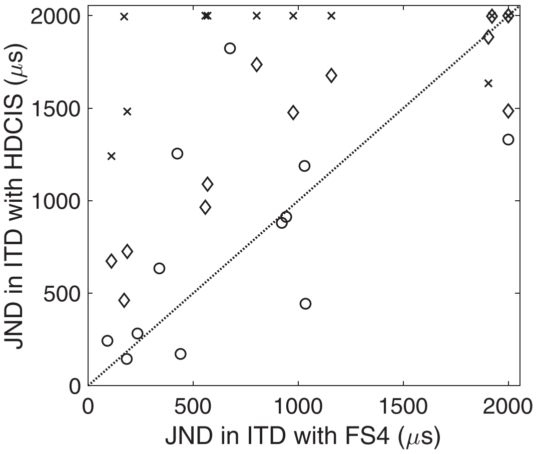


FIG. 2. JNDs in ITDs for the tested coding strategies (FS4 vs HDCIS). Values above the dotted line indicate better performance with the FS4 coding strategy. Circles, diamonds, and crosses indicate JNDs found with pink noise, 250 Hz pure-tones with 100 ms rise/fall times and 250 Hz pure-tones with 10 ms rise/fall times, respectively.

For the 250 Hz frequency stimulus with 100 ms rise and decay times, FS4 again significantly improved the ITD thresholds ($p < 0.01$, $W = 0$, $N = 12$) (HDCIS: 1863 μs, SD = 261 μs, IQR = 1815–2000 μs; FS4: 1231 μs, SD = 808 μs, IQR = 501–1999 μs; normal-hearing listeners: 93 μs, SD = 128 μs, IQR = 30–93 μs).

None of the subjects achieved JNDs below 700 μs with HDCIS, while 5 out of the 12 subjects were able to perceive ITDs below this threshold with the FS4 strategy. The physiological JND-ITD limit of T/2 was exceeded for 8 subjects with the HDCIS strategy compared to 3 subjects with the FS4 strategy.

For the HDCIS coding strategy and the pure-tone stimuli test condition, significantly lower ITD-JNDs with 10 ms rise and decay times compared to ITDs with 100 ms rise and decay times were measured ($p < 0.01$). This difference was not observed for the FS4 coding strategy ($p = 0.36$).

For pink noise stimuli, subjects using the FS4 coding strategy achieved similar results as with the HDCIS coding strategy ($p = 0.62$, $W = 32$, $N = 12$). The measured ITD-JNDs with the HDCIS strategy were 776 μs (SD = 544 μs,

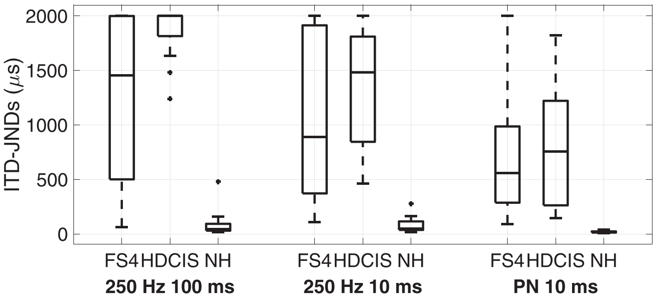


FIG. 3. JNDs in ITDs for the tested coding strategies (FS4 vs HDCIS) and the normal-hearing (NH) participants. The test stimuli used were 250 Hz pure-tones with 100 ms rise/fall times, 250 Hz pure-tones with 10 ms rise/fall times and pink noise with 10 ms rise/fall times. On each box, the central mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively.

IQR = 263–1221 μs) compared to the results with the FS4 strategy of 693 μs (*SD* = 535 μs, *IQR* = 287–986 μs) normal-hearing listeners: 19 μs (*SD* = 9 μs, *IQR* = 13–24 μs). Using the FS4 strategy, seven out of the 12 BiCI subjects had a sensitivity substantially better than the physiological threshold of 700 μs compared to 6 out of the 12 subjects using the HDCIS strategy. The JND-ITD test limit of 2000 μs was exceeded only for 1 subject using the FS4 strategy. A summary of the results is provided in the supplementary material.[1]

B. Detection of binaural beats

All BiCI users detected monaural beats reliably, regardless of the coding strategy used. In terms of BB detection rate, however, BiCI users only significantly exceeded the level of chance rating (33%) for the 135 Hz stimuli and the FS4 coding strategy ($p < 0.01$). For the 135 Hz stimuli, BiCI users achieved a detection rate of 46% (*SD* = 40%, *IQR* = 13%–88%) with the FS4 coding strategy and a detection rate of 29% (*SD* = 25%, *IQR* = 6%–44%, $p = 0.15$) with the HDCIS strategy. In all remaining test conditions (i.e., 250 and 500 Hz pure-tone stimuli), the detection of BBs was not possible for the BiCI users either with the FS4 or the HDCIS strategy. Detailed BB detection results for all stimuli and coding strategies are summarized in the supplementary material.[1]

On the subject level, large differences in the BB detection rates were observed. Some BiCI users could not detect any BBs, while others identified all BBs. Four BiCI users could correctly detect all BBs at 135 and 250 Hz using the FS4 coding strategy. Only one of these four subjects also detected all BBs for 250 Hz stimuli using the HDCIS strategy. This subject was also the only one who detected all BBs at 500 Hz, but only when using the HDCIS coding strategy.

The normal-hearing listeners recognised all stimuli correctly, except for one subject who could not even recognise monaural beats.

C. Static sound source localization

The $\mathrm{RMSE_{LOC}}$ averaged across all BiCI users was comparable for the HDCIS (28°, *SD* = 7°, *IQR* = 23°–34°) and FS4 (28°, *SD* = 6°, *IQR* = 22°–33°) strategies when FBCs were excluded ($p = 0.78$, $W = 35$, $N = 12$).

Similarly, no differences of the $\mathrm{RMSE_{LOC}}$ were observed when FBCs were included in the error analysis (HDCIS: 52.7°, *SD* = 14.7 °, *IQR* = 39.6°–64.7° vs FS4: 52.2°, *SD* = 12.6°, *IQR* = 40.4°–61.5°, $p = 0.79$, $W = 35$, $N = 12$). Half of the subjects performed better with FS4 and the other half with HDCIS. Figure 4 shows the absolute localization accuracy for each azimuth with the HDCIS and FS4 coding strategies.

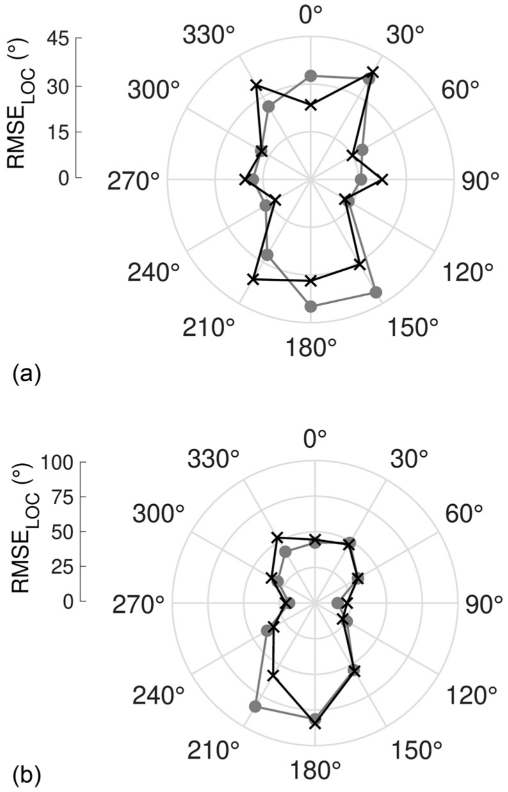


FIG. 4. Averaged root mean square error ($\mathrm{RMSE_{LOC}}$, in degree angle) for static sound localization with the TFS discarding (HDCIS, circles) and preserving (FS4, crosses) coding strategies. (a) Front-back confusions (FBCs) were excluded from the error calculation whereas (b) shows the $\mathrm{RMSE_{LOC}}$ values including FBCs. The azimuth 0° defines the centre of the head in the frontal viewing direction.

The FBC rate was comparable for both strategies [HDCIS: 37%, *SD* = 16%, *IQR* = 20%–53% vs FS4: 36%, *SD* = 14%, *IQR* = 23%–48%, $X^2(1, N = 2) = 0.198$, $p = 0.656$]. The same applied for the FBC score (HDCIS: 19%, $SD = 11\%, IQR = 8\% - 30\%$ vs FS4: 18%, *SD* = 9%, *IQR* = 10%–24%, $p = 0.97$, $W = 38$, $N = 12$). When FBC-associated errors were included in the analysis, the most substantial impact on the $\mathrm{RMSE_{LOC}}$ was observed at the 180° measurement position for the FS4 coding strategy (difference in $\mathrm{RMSE_{LOC}}$ of 53°) and at 210° measurement position for the HDCIS strategy (difference in $\mathrm{RMSE_{LOC}}$ of 57°). Normal-hearing listeners achieved an $\mathrm{RMSE_{LOC}}$ of 13°, *SD* = 4°, *IQR* = 10%–16° (Fischer *et al.*, 2020b). A detailed summary of the FBC analysis is given in the supplementary material.[1] Histograms for the distribution of all responses for both coding strategies can be found in the supplementary material.[1]

D. Minimum audible angle

Figure 5 shows the MAA results for both coding strategies averaged across all subjects. We did not observe differences in the MAA performance between the tested coding strategies. The overall MAA across azimuths was 19.0°, *SD* = 10.2°, *IQR* = 12.2°–25.0° with the HDCIS strategy and 20.8°, *SD* = 6.6°, *IQR* = 15.9°–23.0° with the FS4 strategy ($p = 0.12$, $W = 19$, $N = 12$). As reference, the normal-hearing listeners achieved an MAA of 3.6°, *SD* = 1.6°, *IQR* = 2.3°–4.9° (Fischer *et al.*, 2020b). Independent of the coding strategy, the discrimination was best at the front (0°) followed by the back

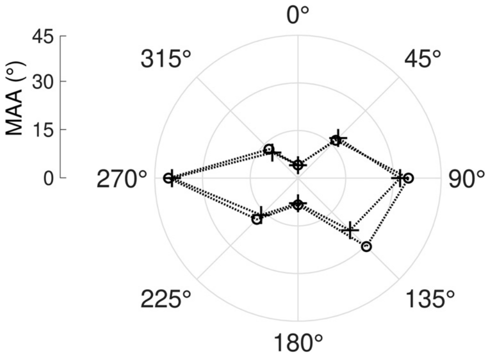


FIG. 5. Minimum audible angle (MAA) performance with the TFS discarding (HDCIS, circles) and preserving (FS4, crosses) coding strategies averaged over all subjects. The azimuth 0° defines the centre of the head in the frontal viewing direction.

(180°), while the worst discrimination was measured at the right (90°) and left side (270°). For both coding strategies, the MAA was significantly smaller at frontal azimuths (315°, 0°, 45°) than at rear azimuths (135°, 180°, 225°; HDCIS: $p = 0.03$, $W = 12$, $N = 12$ and FS4: $p = 0.01$, $W = 8$, $N = 12$). As expected, the discrimination performance between left (225°, 270°, 315°) and right azimuths (45°, 90°, 135°) was comparable (HDCIS: $p = 0.93$, $W = 37.5$, $N = 12$ and FS4: $p = 0.43$, $W = 28$, $N = 12$). A tabular summary of the MAA results can be found in the supplementary material.[1]

E. Sound source tracking

Figure 6 illustrates the azimuthal sound source position, the corresponding subject response, and the resulting source tracking errors. No significant differences in tracking error ($\mathrm{RMSE}_{\vartheta}$) between the two coding strategies were observed in the tracking experiments (HDCIS: 58°, $SD = 14°$, $IQR = 49°–68°$ vs FS4: 61°, $SD = 20°$, $IQR = 40°–77°$; $p = 0.46$, $W = 29$, $N = 12$). In the same experiment, normal-hearing listeners achieved an $\mathrm{RMSE}_{\vartheta}$ of 19°, $SD = 5°$, $IQR = 14°–24°$ (Fischer *et al.*, 2020b). Further details of the tracking experiment results are provided in the supplementary material.[1] The individual subject responses are also shown in the supplementary material.[1]

F. Subjective evaluation

The subjective SSQ spatial hearing domain scores showed a small but statistically significant difference between the HDCIS (5.7, $SD = 1.0$, $IQR = 5.1–6.3$) and FS4 (5.4, $SD = 0.9$, $IQR = 4.8–5.6$, $p = 0.02$, $W = 5.5$, $N = 12$) coding strategies (normal-hearing subjects: 8.6, $SD = 1.0$, $IQR = 7.7 - 9.5$). For the speech domain, no differences between the coding strategies (HDCIS: 6.1, $SD = 1.9$, $IQR = 4.9–7.7$ vs FS4: 6.3, $SD = 1.8$, $IQR = 4.8–7.6$, $p = 0.40$, $W = 23$, $N = 12$) were observed (normal-hearing listeners: 8.0, $SD = 1.3$, $IQR = 7.1–9.2$). Seven subjects preferred FS4 over HDCIS in terms of speech understanding. For the hearing quality domain, seven of the 12 subjects preferred the FS4 strategy, leading to a non-significant better mean value of 6.9, $SD = 1.7$, $IQR = 6.3 - 8.2$ with FS4 compared to a mean value of 6.6, $SD = 2.0$, $IQR = 5.6–7.8$ with HDCIS ($p = 0.29$, $W = 20.5$, $N = 12$; normal-hearing listeners: 8.9, $SD = 0.8$, $IQR = 8.4–9.8$). A summary of the SSQ results is provided in the supplementary material.[1]

After the study, eight of the 12 subjects decided to change the HDCIS coding strategy, to which they had become accustomed for two weeks during the study, back to the FS4 coding strategy. Two subjects wanted to continue using both coding strategies, and only two subjects chose to keep the HDCIS coding strategy. The main reason was that they found environmental noise with HDCIS less disturbing. Interestingly, the same two subjects did not benefit from the FS4 coding strategy in the ITD experiments and showed generally worse performance in the sound localization and discrimination tasks.

G. Correlation analysis

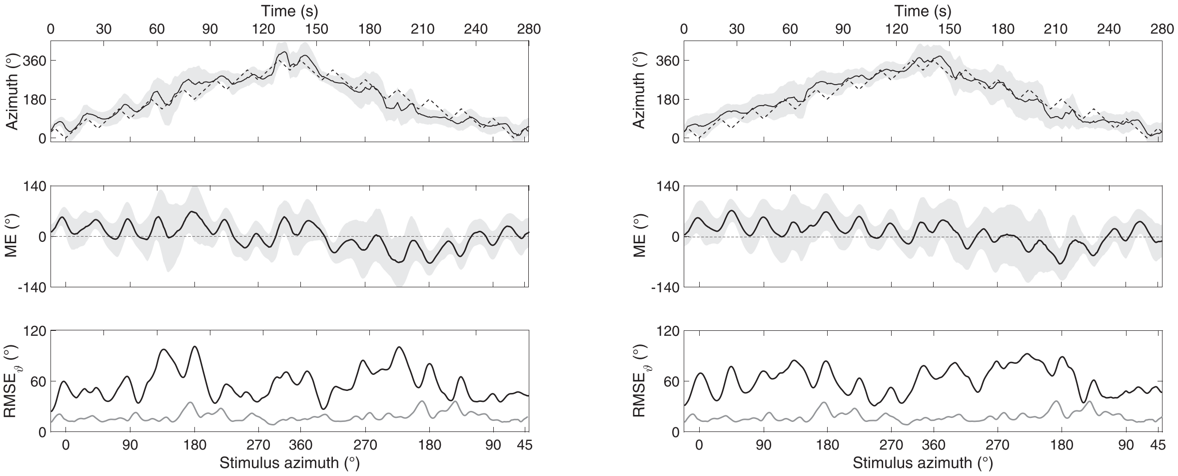
We did not find statistically significant correlations between the headphone-based tests' outcomes and the sound field localization, discrimination, and tracking tests. The subjective assessment of auditory perception with the SSQ also showed no correlation with the experiments' performance. However, for both coding strategies a positive correlation was observed between the hearing experience of CI users in years (averaged over both ears) and their overall SSQ scores [HDCIS: $r(10) = 0.70$, $p = 0.01$; FS4: $r(10) = 0.70$, $p = 0.01$]. The scatter plots can be found in the supplementary material.[1]

In the sound field spatial hearing tasks, a positive correlation between the $\mathrm{RMSE}_{\mathrm{LOC}}$ and the MAA was observed with both coding strategies [HDCIS: $r(10) = 0.79$, $p < 0.01$; FS4: $r(10) = 0.71$, $p = 0.02$]. Taking into account a multiple comparisons Bonferroni correction (test family: $\mathrm{RMSE}_{\mathrm{LOC}}$, MAA, $\mathrm{RMSE}_{\vartheta}$) this correlation was statistically significant. The scatter plots can be found in the supplementary material.[1]

The difference of the electrodes' insertion depths between the left and the right cochlea and the ITD-JNDs did not correlate ($p > 0.05$ for all test stimuli conditions).[1] Insertion depths measurements were only available for the CI users with the subject IDs 04, 06, 07, 08, 11.

VI. DISCUSSION

This study presents a comprehensive analysis to what extent BiCI users can exploit ITD cues provided by a TFS coding strategy (FS4) in a series of sound field spatial hearing tests. The main result of our study is that the TFS cues in the FS4 strategy were perceived by the BiCI users only for the pure-tone stimulus in the JND for ITDs test. For spatial hearing tasks in the sound field, the results of our experiments suggest that either envelope ITD or ILD cues played a more dominant role than TFS cues [e.g., Seeber and Fastl (2008) and van Hoesel and Tyler (2003)]. Consequently, the performance of sound localization, discrimination, and



(a)

(b)

FIG. 6. Sound source tracking with the alternating movement trajectory, including multiple changes in direction. Plotted are the positions of the sound source and the averaged subject responses (as indicated with the touchpad), the mean error (ME), and the root mean square error (RMSE$_\vartheta$) averaged across all the subjects for the TFS discarding [(a) HDCIS] and preserving [(b) FS4] coding strategies. The dashed lines in the top plots show the trajectory of the stimulus, and the solid lines show the averaged stimulus position indicated by the subjects. The gray margins around the solid lines in the top and middle plots indicate ±1 standard deviation. The gray lines in the bottom plots indicate the performance of the normal-hearing subjects. The data in all plots was smoothed using a moving average filter with a length of 2 s.

tracking with pink noise stimuli in our experiments did not differ between the two coding strategies.

Apart from ILD or envelope cues van Hoesel *et al.* (2008), other factors might have influenced the results of the sound-field spatial hearing tasks with FS4 compared to HDCIS. For instance, it is a well-established finding that high stimulation rates (>250 pps), corresponding approximately to the centre frequency of the bandpass for the second most apical electrode of the four TFS preserving electrodes, may have contributed to the lack of advantage from TFS-ITDs in the sound-field tasks (Laback *et al.*, 2015).

Another reason for the lack of effect could be the different insertion depths of the electrodes, which lead to different places of stimulation along the cochlea from electrodes of the same number across the ears. The studies of Kan and Litovsky (2015) and Poon *et al.* (2009) have shown that a mismatch of electrode insertion depth may lead to reduced ITD sensitivity. In this study, radiographic data were only available for 5 of 12 CI users. Therefore, the difference in the insertion depths between the left and the right cochlea could only be calculated for five subjects. No relation between the insertion depth mismatch and the ITD-JNDs was observed in the present study.

A. Headphone-based experiments

In our headphone-based experiments, BiCI users were able to utilize the TFS cues provided by the FS4 coding strategy. The review of Laback *et al.* (2015) reports mean ITD thresholds of 144 μs for CI users stimulated with unmodulated pulse trains (100 pps) on place-matched electrodes. These conditions are considered to provide the best possible ITD thresholds. Indeed, the mean of the ITD thresholds measured in this study were considerably higher. Nevertheless, the measured thresholds are comparable to those of previous studies using comparable conditions [e.g., Gifford *et al.* (2014) and Grantham *et al.* (2008)]. In addition, these studies also report a high variability in ITD-JNDs and subjects without sensitivity to ITDs.

Notably for the detection of ITDs, the FS4 strategy outperformed the HDCIS strategy, in particular with 250 Hz pure-tones. In Klein-Hennig *et al.* (2011), it was hypothesized that shorter temporal ramps allow CI listeners to use onset- and offset-ITDs. We were able to confirm this in our study for the results with the HDCIS coding strategy, where the subjects had statistically significant better ITD thresholds for pure-tones with a 10 ms rise time compared to a 100 ms rise time. For BiCI users with the FS4 strategy, no significant differences were observed in the JND-ITDs with 10 ms rise and fall time compared to the JND-ITDs with 100 ms rise and fall time. This result suggests that using the FS4 strategy, TFS-ITDs mitigated the relative influence of onset and offset ITD cues on the JND-ITDs and led to the overall lower JND-ITDs with the FS4 strategy compared to the HDCIS coding strategy. In Laback *et al.* (2007) unmodulated pulse trains were used at various pulse rates, showing that both onset/offset and ongoing (i.e., fine structure) cues contribute at approximately the rate used in the present study.

With the pink noise stimulus, no differences between the ITD thresholds between the two coding strategies could be found, and the thresholds were overall smaller compared to the thresholds measured with pure-tone stimuli. The results suggest that performance was mediated by temporal envelope cues conveyed at the basal channels that provide good envelope sampling. In addition, pink noise stimuli activate a greater number of CI stimulation channels compared to pure-tone stimuli. This is particularly relevant when considering the results of Ihlefeld *et al.* (2014), who showed that the place-of-stimulation with lowest ITD-JND is predictive of ITD-JNDs with multiple places-of-stimulation. Therefore, it is reasonable to assume that the greater number of channels activated by pink noise increased the probability of one place-of-stimulation having a low ITD-JND. As a result, lower ITD-JNDs with pink noise compared to the pure-tone ITD-JNDs were measured in this study.

The stimulation patterns of BBs with the HDCIS and the FS4 strategy modeled in Zirn *et al.* (2016) suggest, that the preservation of low-frequency TFS-ITDs with the FS4 strategy may provide benefits in the perception of dynamic ITDs. Indeed, in the present study, only BiCI users with the FS4 coding strategy that were tested on the lowest frequency test stimulus (135 Hz) detected BBs significantly above the tests' chance level. This result provides compelling evidence that TFS preserving strategies are necessary for BB sensitivity, though only in a small subset of stimuli.

Previously performed experiments which investigated the perception of dynamic ITDs used single-electrode stimulation and different signal durations and are therefore not directly comparable to the results obtained in this study (Todd *et al.*, 2019; van Hoesel, 2007; Zirn *et al.*, 2016). While single-electrode experiments are meaningful to probe physiological limits, we aimed to provide data under more life-like test conditions. Therefore, we used commercially available speech processors and coding strategies in our BB detection task. The detection rates for any BB test stimulus with the FS4 coding strategy did not differ significantly from the detection rates when the HDCIS coding strategy was used. Thus, the results of our BB detection task suggest that the TFS coding strategy (FS4) does not provide significant benefits in the perception of dynamic ITDs compared to a TFS discarding coding strategy (HDCIS).

Presumably BBs result from central auditory processing of binaurally sensitive neurons (Kuwada *et al.*, 1979). Therefore, sensitivity to BBs is reflective of binaural processing and a BB detection task may serve as a simple diagnostic tool (Dirks *et al.*, 2020). For a part of the BiCI users, we observed the perception of BBs with no significant differences between the two coding strategies. The here measured results raise the question if only pulsating BB perception was used to solve the test. Only one subject was sensitive to BB for 500 Hz with the HDCIS coding strategy; for 135 Hz only with FS4 and for 250 Hz it detected all BB with both coding strategies. The subject might have distinguished the ΔF between the two presented frequencies at both ears. To mitigate the possibility of the usage of pitch to complete the BB task, a JND for frequencies test was performed.[1] The results of the JND for frequencies test showed that no BiCI user was able to distinguish the shift of ΔF presented for the BB test. Nevertheless, future BB tests should be slightly adapted to present only $F_{BB} \pm \frac{1}{2}\Delta F$ to minimise the risk of discriminating the correct response without perceiving BBs.

Although the perceptual strength of BBs is considered relatively weak (Grose *et al.*, 2012), the normal-hearing listeners in our study showed reliable perception except for one participant. This participant did not even correctly identify all monaural beats but showed good ITD-JNDs. The reasons for the bad BB detection rate of this participant remain unclear.

In this study, significantly lower JNDs for the pink noise ITDs were measured. Further experimental research should investigate if this is reflected in higher BB detection rates for shifted noise cues as proposed in Akeroyd (2010).

B. Sound field experiments

We did not observe differences in static sound localization performance between the coding strategies FS4 and HDCIS. This result indicates that the accessibility to low-frequency ITDs which manifest as TFS cues did not provide additional information under our test conditions applying broadband stimuli (pink noise). This finding supports the hypothesis that ILD cues play a dominant role for sound localization in CI listeners using stimulation strategies proposed so far [e.g., Seeber and Fastl (2008), van Hoesel *et al.* (2008), and van Hoesel and Tyler (2003)].

Our results confirm the work of Heidekrüger *et al.* (2019), who did not observe performance differences between the FS4 and HDCIS coding strategies in frontal azimuth-covering sound localization experiments. In contrast to the presented study, no re-fitting of the apical electrodes was performed in Heidekrüger *et al.* (2019) when the coding strategy was changed. Furthermore, the tests with the new coding strategy in Heidekrüger *et al.* (2019) were performed without accommodation and only 3 of the 4 participants used either the fine structure preserving (FSP) sampling or the FS4 coding strategy prior to participation in the study.

The averaged localization errors for the frontal azimuths were in the range of the results as measured in Jones *et al.* (2016) and Dorman *et al.* (2018), who reported an RMSE_{LOC} of 29° and 25°. In the present study, RMSE_{LOC} values of 23° (FS4) and 22° (HDCIS) were observed for the frontal azimuth.

Majdak *et al.* (2011), who tested in the front and rear azimuth, reported RMSE_{LOC} values ∼7° lower, which can be attributed to the trial-by-trial feedback during the measurements. In line with the study of Majdak *et al.* (2011), small errors were measured at lateral azimuths. An analysis of the histograms showing the frequency of responses within the azimuths indicated that for both coding strategies, the tested BiCI users tended to perceive the direction more on the sides than at the front or the back.[1] This response distribution may explain the small errors we measured at the sides. In sound localization studies that restricted the stimulus presentation to frontal azimuths, higher errors were observed at the sides compared to the errors at frontal loudspeaker positions [e.g., Gifford *et al.* (2014), Jones *et al.* (2016), and van Hoesel and Tyler (2003)]. In Jones *et al.* (2016), the smaller errors at the sides were explained by the higher ILD values occurring for sound sources at these azimuths. It remains unclear to what extent the difference in test conditions between a 360° and a 180°-spanning loudspeaker setup influenced the measured localization errors. Because the resolution of FBCs typically exploits spectral pinna cues (Blauert, 1997; Fischer *et al.*, 2021), no significant difference for this error type was expected and observed between the two coding strategies tested in this study.

Overall our MAA measurements agree well with the results of Senn *et al.* (2005) and Mantokoudis *et al.* (2011). The MAAs were smallest at the front and back directions (0° and 180°) and largest on the sides (90° and 270°), most likely due to FBCs (Fischer *et al.*, 2021). Similar to the static localization tests results, we observed no differences in sound discrimination performance between the coding strategies used. As with sound source localization, we assume that the sound discrimination of broadband stimuli is dominated by ILD cues.

In agreement with the other sound field experiments, the tracking performance for the tested trajectory did not differ significantly between the tested coding strategies. We therefore assume that TFS cues play a subordinate role compared to ILDs concerning the tracking ability of a sound source. As in Moua *et al.* (2019), who investigated tracking of virtual sound sources in the frontal azimuth, we observed a higher variability and a significantly lower accuracy in the performance among BiCI users compared to normal-hearing listeners.

In summary, our results showed that the availability of TFS cues to BiCI users as provided by the FS4 strategy did not result in statistically significant improvements of spatial hearing performance with broadband noise stimuli in the sound field. We assume that across-channel interference between multiple stimulation electrodes for broadband stimuli used in the sound field tasks might explain the lacking transfer of advantage by the TFS coding strategy (Laback *et al.*, 2015). To further investigate a possible advantage in sound field localization with a TFS coding strategy, we suggest using pure-tone stimuli below 1.5 kHz. Although pure-tones do not represent everyday listening situations, it is known that at these frequencies, sound localization depends on the ITD arising from disparities in the TFS (Wightman and Kistler, 1997).

C. Subjective evaluation

For the subjective evaluation of the coding strategies with the SSQ, the BiCI users showed no clear preference for a TFS preserving or discarding strategy in everyday listening scenarios.

D. Limitations

Since the study design required subjects to perform the identical tests twice, the results of the sound field tests in the second session using the HDCIS coding strategy could be confounded with a training effect. However, a counterbalanced study session design with identical familiarization periods to the coding strategies was not feasible because all subjects were accustomed to a TFS coding strategy for at least 1 year before participation.

It is well-known that CI users primarily rely on ILDs for sound localization tasks [e.g., Aronoff *et al.* (2010), Dorman *et al.* (2014), and Seeber and Fastl (2008)]. In several studies [e.g., Archer-Boyd and Carlyon (2019), Potts *et al.* (2019), van Hoesel *et al.* (2002), and Wiggins and Seeber (2012)] it was shown that static and dynamically changing ILD cues maybe disrupted by the processor's AGC, which may be detrimental to sound source localization and tracking performance. However, since this study' focus was to investigate the effect of a TFS coding strategy on spatial hearing under everyday processor setting conditions, the AGC was not disabled. For the same reason, a subjective loudness balancing was performed as part of the clinical fitting routine (see Sec. VI B), which may result in differing loudness growth between electrodes or ears [e.g., Fitzgerald *et al.* (2015) and Goupell *et al.* (2013)].

For the BiCI users, the ITD-JND task was subject to a limitation at very large ITDs, because the used adaptive method Shen and Richards (2012) models a monotonic psychometric function. Thus, the procedure was susceptible to be "trapped" at ITDs approaching T/2 where the BiCI users' psychometric function might go down. Since the degree of lateralization was not measured in the ITD-JND task, it remained unclear whether the BiCI users perceived testing at ITDs approaching T/2 as "easier" or "more difficult" compared to slightly smaller ITDs. Moreover, the 35 steps applied in the ITD-JND led to inaccurate, i.e., too steep estimates of the slope-parameter β (Shen and Richards, 2012). However, the expected variance of α decreases with an increase in the slope of the psychometric function Shen and Richards (2012). Exemplary plots of the resulting psychometric functions can be found in the supplementary material.[1]

VII. CONCLUSION

This study provided an overview of the performance in auditory spatial perception with a TFS coding strategy (FS4) compared to a continuous interleaved sampling strategy (HDCIS) in bilateral cochlear implant (BiCI) users with everyday processor settings. The results of our pure-tone headphone-based ITD-JND tests suggest that the BiCI users benefited from the TFS coding strategy. However, the benefits were not transferred to sound field source localization, discrimination, and tracking performance with broadband test stimuli. Given the additional finding that ITD-JNDs for broadband stimuli did not differ between the FS4 and HDCIS strategies, we conclude that besides the perceptual dominance of ILD cues in electric hearing, the availability of envelope ITD cues and the across-channel interference between stimulation electrodes might have prevented performance advantages of TFS coding for broadband stimuli.

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[1] See supplementary material at https://www.scitation.org/doi/suppl/10.1121/10.0005732 for alternative and partly more detailed forms of presentation of the data.

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