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1 **Sensorineural hearing loss alters auditory discrimination of natural** 2 **soundscapes**

3

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15

16 **Abstract**

17 **Objective:** The ability to discriminate natural soundscapes recorded in a temperate terrestrial
18 biome was measured in 15 hearing-impaired (HI) listeners with bilateral, mild to severe
19 sensorineural hearing loss and 15 normal-hearing (NH) controls.

20 **Design:** Soundscape discrimination was measured using a three-interval oddity paradigm and
21 the method of constant stimuli. On each trial, sequences of 2-second recordings varying the
22 habitat, season and period of the day were presented diotically at a nominal SPL of 60 or 80 dB.

23 **Results:** Discrimination scores were above chance level for both groups, but they were
24 poorer for HI than NH listeners. On average, the scores of HI listeners were relatively well
25 accounted for by those of NH listeners tested with stimuli spectrally-shaped to match the
26 frequency-dependent reduction in audibility of individual HI listeners. However, the scores of HI
27 listeners were not significantly correlated with pure-tone audiometric thresholds and age.

28 **Conclusions:** These results indicate that the ability to discriminate natural soundscapes
29 associated with changes in habitat, season and period of the day is disrupted but it is not
30 abolished. The deficits of the HI listeners are partly accounted for by reduced audibility. Supra-
31 threshold auditory deficits and individual listening strategies may also explain differences
32 between NH and HI listeners.

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34 **Keywords:** Natural soundscape; discrimination; cochlear damage; audibility; supra-threshold
35 deficits; listening strategies; age

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1 1. INTRODUCTION

2 Over the last decades, a wealth of research in soundscape ecology demonstrated
3 repeatedly that “natural soundscapes”, that is complex arrangements of sounds produced by
4 biological and geophysical sources shaped by (natural) habitat-specific sound propagation
5 effects, reflect important ecological processes, such as presence of living beings and changes in
6 biodiversity (e.g., Pijanowsky et al., 2011; Sueur & Farina, 2015; Farina & Gage, 2017; Sugai et
7 al., 2018; Sethi et al., 2020; for a review see Grinfeder et al., 2022). Two recent studies revealed
8 that normal-hearing (NH) people show high sensitivity for natural soundscape discrimination
9 (e.g. forest, grassland), and perceive relatively well changes across habitats and their diel and
10 seasonal variations (Thoret et al., 2020; Apoux et al., 2023). This capacity to build a “perceptual
11 soundscape” (Grinfeder et al., 2022) should be useful for mapping the nearby environment,
12 navigating, assessing resources and danger, or building a sense of place and time (Fay, 2009).
13 However, despite the high adaptive and psychological value of processing natural soundscapes,
14 very little is known about the acoustic cues and mechanisms at work. This is true not only for
15 typical hearing but also for all forms of hearing disorders. To our knowledge, most of the efforts
16 in audiology have been devoted to the study of speech perception in urban settings (e.g., when
17 speech is presented against interfering speaker(s), traffic or cafeteria/restaurant noise, or uttered
18 in reverberant rooms, etc.; for a review, see Moore, 2007) and, to a lower extent, the study of
19 auditory perception of isolated environmental – and mostly urban – sounds (Shafiro et al., 2022).
20 Therefore, the effects of sensorineural hearing loss on natural soundscape perception are
21 unknown. This is quite surprising given the numerous benefits of exposure to natural sounds,
22 such as improved health and cognitive outcomes, positive affects and decreased stress and
23 annoyance (for reviews, see Buxton et al., 2021, and Ratcliffe, 2021). These effects are typically

1 coined as “restorative” as they were shown to be associated with recovery from physiological
2 (autonomic) stress and attentional fatigue (e.g., Gould van Praag et al., 2017), and more
3 generally, increased well-being (e.g., Fuller et al., 2007; Ferraro et al., 2020). At least one study
4 based on a questionnaire indicated that people with hearing problems (i.e., tinnitus, sensorineural
5 hearing loss) show less restorative effects than normal-hearing people when visiting urban parks
6 (Payne, 2008a,b). Thus, for hearing-impaired (HI) individuals living in rural environments,
7 working or visiting regularly natural areas such as green spaces and national parks, quality of life
8 may not only depend on efficient communication, but also on accurate perception of their
9 environment including natural soundscapes and their changes across the day and seasons. This
10 needs to be taken seriously in view of the fact that about half of the world’s population still lives
11 in rural environments (UN World cities report, 2022), and substantial efforts are made to offer
12 city-dwellers with limited contact with nature the possibility to regularly experience natural
13 soundscapes through parks within and outside cities (Kang et al., 2016; Buxton et al., 2021).
14 Hearing aids are expected to rehabilitate some of the auditory deficits associated with
15 sensorineural hearing loss and surveys indicate that satisfaction with hearing aids is strongly
16 related to the listening environment (Kochkin, 2005, 2011). Modern hearing aids now
17 incorporate adaptive environment classification algorithms (e.g., Kates, 1995; Lamarche et al.,
18 2010; Hayes, 2021), however, these algorithms have been mostly designed and tested for urban
19 settings, and large differences appear across manufacturers’ products for complex environments
20 (Yellamsetty et al., 2021). It is therefore unclear whether such algorithms would benefit natural
21 soundscape perception. It is also unclear whether the nonlinear amplification provided by
22 hearing aids would improve or disrupt natural soundscape perception. Altogether, these elements
23 call for an in-depth exploration of HI listeners’ perception of natural soundscapes.

1 The goal of the present study was to assess natural soundscape discrimination for
2 listeners with bilateral mild-to-severe sensorineural hearing loss between 0.25 and 8 kHz. The HI
3 listeners were tested using a database of acoustic recordings from a temperate terrestrial biome:
4 the biosphere reserve of the Sequoia National Park in the USA (Krause et al., 2011). The
5 recordings were made in four distinct habitats – a riparian forest, a meadow, a chaparral and a
6 grassland, all depicted in figure 2 – during four seasons and four periods of the day. For each
7 listener, soundscape discrimination was measured using an oddity paradigm. This study extends
8 a previous psychophysical study conducted with NH listeners (aged from 22 to 40 years) using
9 the same database and the same experimental paradigm (Apoux et al., 2023).

10 The auditory deficits reported in the literature for HI listeners have been typically
11 explained in terms of (i) elevated audiometric thresholds and the associated frequency-dependent
12 reduction in audibility, and (ii) supra-threshold auditory deficits in the spectral and temporal
13 analysis of sounds (see Moore, 2007). Several supra-threshold auditory deficits have been
14 identified, such as reduced frequency selectivity, enhanced temporal-envelope sensitivity
15 resulting from loudness recruitment, and reduced ability to process temporal fine structure cues
16 (the rapid fluctuations in amplitude close to the center frequency of a narrow-band signal). An
17 approach often employed to tease apart the contribution of reduced audibility and supra-
18 threshold auditory deficits is to match each HI listener with at least one NH listener tested with
19 stimuli spectrally-shaped to match the frequency-dependent reduction in audibility of that HI
20 listener.

21 Aging leads to supra-threshold deficits (Gordon-Salant et al., 2010), that in turn affect
22 speech intelligibility in quiet and in noise, independently of any loss of audibility as measured by
23 the pure-tone audiogram (e.g., Dubno et al., 2002; Füllgrabe et al., 2015). However, it is still

1 unclear whether ageing *per se* alters auditory scene analysis (for a review, see Schneider et al.,
2 2010) and thus, soundscape perception. To assess the effects of age on natural soundscape
3 perception, the correlation between age and soundscape discrimination performance was
4 estimated. In addition, soundscape discrimination performance was compared for a sub-group of
5 NH listeners and their age-matched HI listeners.

6

7

8 **2. METHODS**

9 **2.1. Listeners**

10 All listeners were fully informed about the goal of the study and provided written consent
11 before their participation. This study was approved by the national ethical committee CPP Ile de
12 France III (Am8618-1-S.C.3460; N° EUDRACT: 2016-A01769-42).

13 / Insert Figure 1 about here /

14 Fifteen listeners (10 females, 5 males) with a bilateral sensorineural hearing loss
15 participated in the study. They were recruited through the ENT department of the Institute Arthur
16 Vernes in Paris. Audiometric thresholds were measured in each ear at 0.25, 0.5, 1, 2, 4 and 8 kHz
17 before running the psychophysical experiments. The listeners' gender, age and pure-tone average
18 (PTA in dB HL: audiometric thresholds averaged across ears at 0.25, 0.5, 1, 2, 4 and 8 kHz) are
19 reported in Table 1. This estimate of PTA was preferred to the more conventional estimate of
20 PTA, calculated by averaging the audiometric thresholds across ears at 0.5, 1 and 2 kHz only
21 (Goodman, 1965), as the latter, ignoring the contribution of higher audio frequencies, was on
22 average 7 dB lower. The severity of hearing loss varied widely across listeners with a PTA
23 ranging from 25 to 75 dB HL (mean = 46 dB HL, standard deviation (SD)=13 dB HL). Four HI

1 individuals (HI6, HI7, HI11 and HI13) showed a mild loss (PTA=25, 34, 37 and 30 dB HL,
2 respectively). The remaining HI listeners showed moderate-to-severe losses. Hearing loss was
3 reasonably symmetric for all listeners (see Fig. 1). Three participants (HI3, HI4, HI12) showed a
4 nearly flat pure-tone audiogram, whereas the remaining 12 showed a high-frequency hearing loss
5 above 1-4 kHz. Differences between air- and bone-conduction thresholds ranged from 0 to 10 dB
6 across HI listeners ear at 0.5, 1, 2 and 4 kHz, indicating that the hearing loss was of sensory
7 origin. The HI listeners were aged between 20 and 83 years (mean=62 years; SD=20 years). The
8 degree of loss – as quantified by the PTA – was not significantly correlated with age (Pearson r ,
9 $r=0.04$; $p=0.9$), as would be expected because all participants were not selected from the
10 population of people with age-related hearing loss.

11 Fifteen listeners (7 females, 8 males) with normal (≤ 20 dB HL) audiometric thresholds at
12 0.25, 1, 4 and 8 kHz also participated in the study. NH listeners were aged 18 to 48 years
13 (mean=30 years; SD=7 years). Their gender, age and PTA are reported in Table 1.

14 A mixed-design analysis of variance (ANOVA) was conducted on the individual
15 audiometric thresholds with Group (2 levels: NH and HI) as a between-subject factor and
16 Frequency (4 levels: 0.25, 1, 4 and 8 kHz) and Ear (2 levels: right and left ear) as within-subject
17 factors. The analyses showed that there was a significant effect of Group [$F(1,27)=206.8$;
18 $p<0.0001$] and Frequency [$F(3,81)=29.7$; $p<0.0001$]. There was no significant effect of Ear
19 [$F(1,27)=1.84$; $p=0.19$]. There was a significant interaction between Group and Frequency
20 [$F(3,81)=49.6$; $p<0.0001$], but no significant interactions between Ear and Frequency
21 [$F(3,81)=1.2$; $p=0.32$], Ear and Group [$F(1,27)=0.21$; $p=0.65$], and between Group, Ear and
22 Frequency [$F(3,81)=0.73$; $p=0.54$].

23 Listeners with hearing loss have a skewed age distribution. Most of them were generally

1 older than NH listeners, as confirmed by a Student *t*-test for independent samples conducted on
2 age with Group (NH and HI) as a between-subject factor [$t(28)=5.7$; $p<0.0001$], but still, both
3 groups overlapped to some extent. Eleven HI participants were aged between 59 and 83 years.
4 The remaining four young (HI3: 20 years; HI5: 28 years) and middle-aged (HI6: 34 years; HI2:
5 47 years) HI participants could be matched relatively well with four NH participants (NH3: 23
6 years, NH5: 29 years, NH6: 36 years and NH2: 48 years, respectively) to examine the effect of
7 age on soundscape discrimination.

8

9

10 **2.2. Material**

11 The stimuli, material and procedure used to measure natural soundscape discrimination
12 were identical to those described by Apoux et al. (2023). The spectro-temporal statistics of the
13 natural scenes used in the experiments were described and analyzed in Thoret et al. (2020).

14 *2.2.1. Stimuli*

15 The stimuli were generated from the 64 hours of acoustic recordings collected by Krause
16 et al. (2011) in the Sequoia National Park, an area located in the southern Sierra Nevada,
17 California (USA) and designated as a Biosphere reserve by UNESCO in 1976. Recordings were
18 made in four habitats, at four seasons and four broad periods of the day. Detailed information
19 about habitats, recording conditions and material is provided in Krause et al. (2011). The four
20 habitats, shown in Figure 2, were chosen as they represent unique combinations of elevation and
21 vegetation diversity. The four habitats were: (1) Crescent Meadow (CM), located at 2154 m
22 [N36° 33.364 W118° 44.867], a meadow surrounded by sequoia trees; (2) Shepherd Saddle
23 (SH), located at 925 m [N36° 29.470 W118° 51.142], a dry savannah chaparral with high winds;

1 (3) Buckeye Flat (BF), located at 890 m [N36° 31.185 W118° 45.692], a riparian area crossed by
2 a river producing a relatively loud stream; and (4) Sycamore Springs (SY), located at 645 m
3 [N36° 29.470 W118° 51.225], a foothill site dominated by an oak savannah. The four seasons
4 corresponded to fall (October), winter (January), spring (May) and summer (July). The four
5 periods of the day corresponded to the following times: T1 [0, 5 or 7am], T2 [11 am], T3 [4 or
6 5pm] and T4 [8 or 11pm].

7 / Insert Figure 2 about here /

8 All sounds were originally recorded at a 44.1 kHz sampling rate (two channel; 16 bits;
9 MS [Mid-Side] wav format). They were converted to 22,050 Hz monaural. From this database,
10 90 acoustic samples of 2 seconds were extracted for each combination of habitats, seasons and
11 periods of the day for a total of 5760 2-sec samples (4 habitats x 4 seasons and 4 periods of the
12 day x 90 samples). All samples were tapered by 50-ms raised-cosine ramps and equated in long-
13 term root-mean-square (rms) power to remove idiosyncratic level cues related to recording
14 conditions (*e.g.*, distance from microphone to specific biotic and abiotic sound sources). All
15 stimuli were presented diotically to all listeners through Sennheiser HD650 headphones.
16 Stimulus level was roved by ± 6 dB (in 1-dB steps) within and across trials to limit the use of
17 absolute loudness cues.

18

19 **2.3 Procedure**

20 Listeners' discrimination ability was measured using a forced-choice, 3-interval oddity
21 paradigm (Frijters, 1979, 1981; Versfeld et al., 1996) and the method of constant stimuli. This
22 "odd-one-out" procedure, sometimes referred to as "triangular", paradigm was chosen because it
23 is easy to instruct (participants just need to select the stimuli that is different) and it limits bias.

1 Each testing session consisted of 120 trials. Each trial was made of 3 successive time intervals,
2 one target and two standards, separated by a 1-sec silent inter-stimulus interval for a total of
3 $3 \times 120 = 360$ stimuli per session. Samples were selected without replacement within a testing
4 session so that no stimuli were presented more than once during a session. The target and two
5 standards were presented in random order. Listeners were asked to indicate which interval (the
6 target) differed from the remaining two (the standards) by clicking on a virtual button presented
7 on a computer screen. Visual feedback was given to the listener at the end of each trial. The next
8 trial started 1 second after a listener's response. Every twelve trials, listeners were given a short
9 (silent) 10-second break. Each testing session lasted about 20 minutes.

10 Discrimination abilities were tested in three sessions, each corresponding to a given
11 experimental condition (Habitat, Season, or Period of the day). For each NH and HI listener, the
12 three experimental conditions were tested in random order.

13 1. *a. Habitat-discrimination task.* On each trial, participants were presented with a stimulus
14 recorded in one habitat (*e.g.*, BF) and two stimuli recorded in another habitat (*e.g.*, SY).
15 Each habitat, as target, was contrasted with all other different habitats, as standards,
16 giving 3 combinations total per habitat. All possible combinations of habitats (4 habitats
17 x 3 combinations per habitat) were used during a session. These 12 combinations were
18 presented in random order within the session. Within each trial, the season and period of
19 the day were identical for all 3 stimuli but changed randomly across trials. However, all
20 the participants were presented with the same combinations of season and period of the
21 day. Only the order of presentation of these combinations varied randomly across
22 participants.

1 *b. Season-discrimination task.* On each trial, participants were presented with a stimulus
2 recorded during one season (*e.g.*, fall) and two stimuli recorded in another season (*e.g.*, winter),
3 with the constraint that the two seasons were consecutive (*i.e.*, fall and winter; winter and spring;
4 spring and summer; summer and fall). This aimed to increase the general realism of the task as
5 seasons follow each other. All 4 pairs of consecutive seasons were used during a session. These 4
6 pairs were presented in random order within the session. Within each trial, the habitat and period
7 of the day were identical for all 3 stimuli but changed randomly across trials. However, all the
8 participants were presented with the same combinations of habitat and period of the day. Only
9 the order of presentation of these combinations varied randomly across participants.

10 *c. Period-of-the-day discrimination task.* On each trial, participants were presented with a
11 stimulus recorded during one period of the day (*e.g.*, T1) and two stimuli recorded during
12 another period of the day (*e.g.*, T2), with the constraint that the two periods of the day were
13 consecutive (*i.e.*, T1-T2, T2-T3, T3-T4, and T4-T1). As for season discrimination, this aimed to
14 increase the general realism of the task as dawn, midday, evening and nighttime follow each
15 other. All 4 pairs of consecutive periods of the day were used during a session. These 4 pairs
16 were presented in random order within the session. Within each trial, the habitat and season were
17 identical for all 3 stimuli but changed randomly across trials. However, all participants were
18 presented with the same combinations of habitat and season. Only the order of presentation of
19 these combinations varied randomly across participants.

20 2.3.1. Testing sessions

21 Both NH and HI listeners were tested in the three experimental conditions at a nominal
22 SPL(A) of 60 dB except for one single HI listener who was tested at a higher level of 80 dB
23 SPL(A). This participant (HI4, 73 years) could not hear the stimuli at 60 dB SPL(A) but

1 preliminary testing indicated that he could do so (and reach discrimination scores above chance
2 level in all testing conditions) if level was raised by 20 dB. HI4 was not the oldest participant but
3 he was the one with the worst PTA (75 dB HL). HI4 was included in the experimental protocol
4 because of the relatively small size of the current HI cohort, but statistical analyses were
5 conducted with and without his data.

6 In a subsequent testing session, NH listeners were tested again using the same material
7 and procedure. However, each NH listener was assigned a given HI listener (see Table 2) and the
8 original stimuli were spectrally-shaped and attenuated to reflect the audiometric configuration of
9 the corresponding HI listener. Listener matching was based on age proximity for eight
10 participants (NH2 with HI2; NH3 with HI3; NH5 with HI5; NH6 with HI6). For the remaining
11 listeners, matching was done randomly. Spectral shaping aimed at assessing the effects of
12 audibility on discrimination scores for HI listeners (“Spectral Shaping” or “SS”). The low-
13 frequency pure-tone average (LF-PTA, *i.e.*, the mean audiometric thresholds at 0.25 and 1 kHz at
14 both ears) of each listener was first calculated and the difference between the LF-PTA of the NH
15 and HI listeners forming a pair was used to attenuate the stimuli, re: 60 dB SPL(A). No further
16 processing was applied when the audiometric configuration was considered as “flat” for HI
17 listeners (that is, for HI3, HI4 and HI12). A lowpass (Butterworth) filter was designed when the
18 audiometric configuration was considered as “sloping” (that is for the remaining HI listeners). In
19 that case, a cutoff frequency and roll-off was estimated based on the pure-tone audiogram
20 averaged across ears of the HI listener. Table 2 details the final presentation levels, attenuation
21 and filtering characteristics used for each NH listener. For listeners HI3 and HI4, hearing loss
22 below 2 kHz was so severe that their matching NH listeners could not perform the task. For these
23 NH listeners (NH3 and NH4), attenuation was adjusted manually until they could perform the

1 task: in this specific case, attenuation was reduced by 5 and 11 dB, respectively. This suggests
2 that for NH listeners, the current natural soundscapes could not be discriminated for levels below
3 20-30 dB SPL.

4

5

6 3. RESULTS

7

/ Insert Figure 3 about here /

8

Figure 3 shows the individual discrimination scores of NH and HI listeners for
9 experimental conditions Habitat (top panel), Period of the day (middle panel) and Season
10 (bottom panel), respectively. In each panel, the individual discrimination scores of HI listeners
11 are plotted along those measured for NH listeners using i) the original stimuli presented at 60-dB
12 SPL, and ii) spectrally-shaped (“SS”) stimuli; the rightmost bars show the mean discrimination
13 scores across listeners with standard deviation error bars. The horizontal dashed line shows
14 chance level (33% correct discrimination).

15 3.1. Soundscape discrimination scores: NH versus HI listeners

16

The discrimination scores of HI listeners were always above chance level (33%), the
17 lowest one being listener HI8 in the “Season” condition (35%). Student *t*-tests confirmed that
18 performance was significantly above chance for the group of HI listeners in the three
19 experimental conditions [Habitat: $t(14)=12.1$; $p<0.001$; Season: $t(14)=12.4$; $p<0.001$; Period of
20 the day: $t(14)=9.1$; $p<0.001$]. Interestingly, HI listeners seemed to perform more poorly than NH
21 listeners in each experimental condition (Habitat, Period of the day, and Season). For habitat
22 discrimination, the individual scores of HI listeners ranged from 41 to 63% (mean = 52%; SD =
23 8 percentage points (pp)). In comparison, the individual scores of NH listeners ranged from 52 to

1 78% (mean = 66%; SD = 7 pp). For discrimination of period of the day, individual scores ranged
2 from 41 to 54% for HI listeners (mean = 47%; SD = 7 pp) and from 55 to 69% for NH listeners
3 (mean = 60%; SD = 5 pp). For season discrimination, individual scores ranged from 35 to 58%
4 for HI listeners (mean = 47%; SD = 6 pp) and from 52 to 66% for NH listeners (mean = 59%;
5 SD = 4 pp). On average, performance was 14, 13 and 12 pp lower for HI than for NH listeners
6 for habitat, period of the day and season discrimination, respectively. This is shown on the left
7 panel of Figure 4, which presents the mean discrimination scores across NH and HI listeners,
8 with standard deviation error bars, for all three experimental conditions.

9 / Insert Figure 4 about here /

10 For habitat discrimination, the mean d' score was 1.6 (SD=0.3) for HI listeners *versus* 2.3
11 (SD=0.4) for NH listeners (Versfeld *et al.*, 1996). For discrimination of period of the day, the
12 mean d' level was 1.3 (SD=0.2) for HI listeners *versus* 2 (SD=0.2) for NH listeners. For season
13 discrimination, the mean d' score was 1.3 (SD=0.4) for HI listeners *versus* 1.9 (SD=0.2) for NH
14 listeners.

15 The apparent lower performance of the HI listeners was confirmed by three independent
16 Welch's unequal variances t -test, one for each experimental condition. They can be treated
17 independently because different stimuli were used in each one of them. These analyses showed
18 that HI listeners performed worse than NH listeners in every experimental condition: Habitat
19 [$t(27.76)=-5.91$; $p<0.0001$], Period of the day [$t(27.99)=-7.87$; $p<0.0001$], and Season
20 [$t(24.37)=-6.22$; $p<0.0001$]. The same analyses were performed without listener HI4 who was
21 tested at a higher level of 80 dB SPL(A). The outcome of these additional analyses was similar
22 (Habitat [$t(27)=-5.75$; $p<0.0001$], Period of the day [$t(26.9)=-7.55$; $p<0.0001$], and Season
23 [$t(22.7)=-5.89$; $p<0.0001$]).

1 In the present study, the effects of sensorineural hearing loss were confounded with the
2 effects of age. Figure 3 indicates that for each experimental condition, the discrimination scores
3 of four HI listeners [HI3 (20 years), HI5 (28 years), HI6 (34 years), and HI2 (47 years)] were
4 lower than those measured in their age-matched NH listeners [NH3 (23 years), NH5 (29 years),
5 NH6 (36 years) and NH2 (48 years), respectively], suggesting that sensorineural hearing loss
6 may impair soundscape discrimination independently of the effects of ageing.

7

8 **3.2. Effects of spectral shaping on soundscape discrimination scores**

9 Figure 3 shows that spectral shaping (NH-SS) had a detrimental influence on the
10 individual discrimination scores of NH listeners in each of the three experimental conditions. On
11 average, after spectral shaping discrimination scores decreased by about 12, 8 and 8 pp for
12 habitat, period of the day, and season discrimination, respectively. This is shown on the middle
13 panel of Figure 4 which presents the mean discrimination scores across NH and NH-SS listeners,
14 with standard deviation error bars, for all three experimental conditions.

15 Three repeated-measures *t*-test were computed, one for each experimental condition.
16 They can be treated independently because different stimuli were used in each condition. These
17 analyses showed that the spectral shaping decreased NH listeners performance in every
18 experimental condition: Habitat [$t(14)=5.29$; $p<0.001$], Period of the day [$t(14)=3.93$; $p=0.0015$],
19 and Season [$t(14)=4.53$; $p<0.001$].

20 Figure 3 shows that the discrimination scores of individual NH listeners measured with
21 spectrally-shaped stimuli (NH-SS) did not match those measured in their corresponding HI
22 listener for all pairings; moreover, there was no systematic trend. Although discrimination scores
23 were more often than not better for the NH-SS listeners than for HI listeners (*e.g.*, NH4-SS,

1 NH5-SS, NH8-SS, NH9-SS, NH11-SS, and NH15-SS vs. NH1-SS, NH12-SS, and NH13-SS),
2 they seemed comparable on average as shown on the right panel of Figure 4 which presents the
3 mean discrimination scores across NH-SS and HI listeners, with standard deviation error bars,
4 for all three experimental conditions. This impression was confirmed by three independent
5 Welch's unequal variances *t*-test, one for each experimental condition. They can be treated
6 independently because different stimuli were used in each condition. These analyses showed no
7 significant difference between HI and NH-SS in any experimental condition: Habitat [$t(22,4)=-$
8 $0,50$; $p=0,62$], Period of the day [$t(22,2)=-1,97$; $p=0,062$], and Season [$t(27,9)=-1,51$; $p=0,14$].

9

10 **3.3. Influence of age and audibility on soundscape discrimination**

11 For each experimental condition ((i) Habitat, (ii) Period of the day, (iii) Season), three
12 Pearson-correlation analyses were conducted between discrimination scores of HI listeners and
13 age, PTA, and mid/high-frequency PTA (MF/HF-PTA, the mean audiometric thresholds at 2, 4
14 and 8 kHz, across the two ears). The latter analysis was motivated by the fact that Apoux et al.
15 (2023) showed that NH listeners base their decisions on gross spectral cues located in the
16 mid/high frequency range. For each analysis, the criterion for significance was adjusted using a
17 Bonferroni correction which divides the criterion by the number of comparisons made (3
18 analyses for each experimental condition). Therefore, significance was considered as achieved
19 for $p < 0.05/3 = 0.016$. These analyses did not reveal any significant correlation between age and
20 discrimination scores [(i) Habitat: $r = -0.15$; $p = 0.6$; (ii) Period of the day $r = 0.08$; $p = 0.8$; (iii)
21 Season: $r = -0.17$; $p = 0.6$]. This correlation remains non significant even when reconducted with
22 PTA partialled out [(i) Habitat: $r = -0.15$; $p = 0.6$; (ii) Period of the day $r = 0.12$; $p = 0.7$; (iii) Season:
23 $r = -0.18$; $p = 0.6$]. The analyses also failed to show a significant correlation between PTA and

1 discrimination scores [(i) Habitat: $r=-0.32$; $p=0.25$; (ii) Period of the day $r=-0.5$; $p=0.06$; (iii)
2 Season: $r=-0.57$; $p=0.03$]. Moreover, there was no significant correlation between MF/HF-PTA
3 and discrimination scores [(i) Habitat: $r=-0.17$; $p=0.55$; (ii) Period of the day $r=-0.38$; $p=0.17$;
4 (iii) Season: $r=-0.51$; $p=0.05$].

5 These results suggest that age *per se* did not contribute to the soundscape discrimination
6 deficit demonstrated by the HI listeners and these analyses do not support the idea that reduced
7 audibility has contributed to the soundscape discrimination deficit demonstrated by the HI
8 listeners. The apparent contradiction between this conclusion and the one drawn from the
9 analysis of the NH data collected with spectrally-shaped stimuli is discussed below.

10

11 **4. DISCUSSION**

12 Almost half of the population of the world lives in a rural environment (44.7% up to
13 2018, according to the UN World cities report, 2022). The people living in these environments
14 are subjected to a daily experience of natural soundscapes that are marginally influenced by
15 human activity and can take the form of a chorus of birds, insects and amphibians at dawn or
16 dusk, the hum of flying insects on a hot summer day, the crackle of a light rain, the wind blowing
17 through the trees, the gentle sound of a river or the roar of a waterfall, etc. These natural
18 soundscapes provide a rich source of information that can be used to guess the time of the day
19 through the dawn or dusk chorus and other daily acoustic events, estimate meteorological
20 conditions such as the strength of wind, rain or streams, orientate in a forest or at night time
21 without artificial light, etc. Furthermore, these natural soundscapes are thought to be beneficial
22 for humans' physical and mental health (Buxton et al., 2021, Ratcliffe, 2021). Despite all these
23 psychological and physiological benefits, information is clearly lacking about the cues and

1 mechanisms at work when perceiving natural soundscapes and, to the best of our knowledge,
2 only one study has explored the ability to discriminate natural soundscapes in normal-hearing
3 adults (Apoux et al., 2023). Moreover, the population in developed countries ages and tends to
4 develop hearing difficulties of sensory and cognitive origin associated with ageing (Roth 2011),
5 and it is reasonable to assume that these hearing difficulties have an impact on the daily
6 experience of natural soundscapes, altering the quality of life of people with hearing impairment
7 (e.g., Payne, 2008a,b). Therefore, the goal of the present study was to investigate – for the first
8 time – the effects of sensorineural hearing loss on the ability to distinguish between natural
9 soundscapes and their diel and seasonal changes.

10

11 **4.1. Sensorineural hearing loss yields poorer-than-normal natural soundscape** 12 **discrimination**

13 Fifteen listeners showing mild to severe bilateral sensorineural hearing loss were tested
14 for discrimination of natural soundscapes at a fixed SPL of 60 dB (or 80 dB for one HI listener).
15 On average, HI listeners demonstrated a poorer capacity to discriminate habitat, period of the day
16 and season compared with listeners with audiometrically normal hearing. However, the capacity
17 to discriminate natural soundscapes was not abolished, even for the most severe forms of hearing
18 loss. Interestingly, the magnitude of this deficit was not clearly related to with the audiometric
19 configuration.

20

21 **4.2. Contribution of audibility to the soundscape discrimination deficit of HI listeners**

22 The lower performance of HI listeners was not related to the degree of hearing loss as
23 measured by audiometric thresholds at both ears. More surprisingly, audiometric thresholds

1 measured in the mid-high frequency range (2-8 kHz) known to convey information about
2 biophony and habitat acoustics, and to play a crucial role in the decisions of NH listeners (Apoux
3 et al. 2023) did not predict the performance of HI listeners. Still, simulating reduced audibility in
4 NH listeners similar to that observed in HI listeners altered the performance of NH listeners. At
5 the individual level, spectral shaping did not decrease systematically the performance of NH
6 listeners to the level observed in their corresponding HI listener¹. This may be due to the fact that
7 listeners weight differently the spectral cues in the soundscape discrimination task, as shown by
8 Apoux et al. (2023).

9 The group data provided a clearer picture and the performance of NH listeners tested with
10 spectrally-shaped stimuli was not significantly different from that found in HI listeners.
11 Unfortunately, indicators of cochlear mechanical dysfunction were not collected in the present
12 HI participants. We can therefore only speculate as to whether the loss of the active mechanism
13 in the cochlea and the resulting reduction in audibility did contribute to the deficit demonstrated
14 in HI listeners for natural soundscape discrimination. For the same reason, we can only speculate
15 as to whether the absence of significant correlation between the audiometric data and soundscape
16 discrimination scores is due to the contribution of supra-threshold auditory deficits such as
17 reduced frequency selectivity, temporal processing capacities and central changes in listening
18 strategies. Further work is warranted to assess and compare the auditory cues used by NH and HI
19 listeners in the present tasks.

1 For listeners HI3 and HI4, hearing loss was so severe that their matching NH listeners could not perform the task. For these NH listeners (NH3 and NH4), attenuation was adjusted manually until they could perform the task (see methods section). Therefore, the actual differences in discrimination scores between these two NH listeners and their matching HI participant was smaller than what was measured, suggesting that the role of audibility was stronger than what is reported here for HI3 and HI4.

1 The highest audio-frequency of the present stimuli was limited to 11.025 kHz because of the
2 22.05-kHz sampling rate of the database. Some insect sounds show spectral components well
3 above 10 kHz. This potentially important information was therefore excluded from the present
4 database and unavailable to our NH and HI listeners. Using lowpass or highpass filtered versions
5 of the current stimuli, Apoux et al. (2023) showed that acoustic cues between 4 and 11 kHz have
6 a significant, though modest contribution to habitat discrimination scores compared to acoustic
7 cues in the mid-frequency (2 kHz) region. However, filtering experiments were not run for
8 discrimination of season and moment of the day, so one cannot exclude the possibility that high-
9 frequency cues (>10 kHz) might have contributed to other aspects of soundscape discrimination
10 for NH listeners. Therefore, the specific role of high-frequency information for normal-hearing
11 and hearing-impaired listeners remains an open question.

12

13 **4.3. No contribution of age to the soundscape discrimination deficit of HI listeners**

14 The lower performance of HI listeners was not related to their age. This is consistent with
15 the idea that ageing *per se* spares auditory scene analysis as shown by, for example, experiments
16 assessing the effect of age on the ability to segregate competing speech sources (Humes et al
17 2006; Schneider et al., 2010). It is often assumed that ageing is associated with suprathreshold
18 auditory deficits in the time domain (e.g., Füllgrabe et al., 2015; Wallaert et al., 2016). The
19 current results are therefore consistent with the idea that temporal cues (*i.e.*, temporal fine-
20 structure and temporal-envelope cues) do not play a major role in natural soundscape
21 discrimination.

22

23 **4.4. Implications and future directions**

1 The present study reveals that irrespective of audiometric thresholds, sensorineural
2 hearing loss alters substantially the auditory ability to perceive differences across habitats and
3 their diurnal and seasonal variations. As a consequence, the capacity of HI people to form an
4 image of their close environment is poorer compared to NH people. This may impact their
5 capacity to navigate, assess resources and danger and build “a sense of place and time” (Fay,
6 2009). Moreover, psychological and health benefits of exposure to natural sounds (Buxton et al.,
7 2021; Ratcliffe, 2021) may also be limited and quality of life of individuals with even moderate
8 hearing loss may be diminished. Indeed, many studies suggest that natural environments – and
9 thus natural soundscapes – facilitate recovery from cognitive fatigue and stress and contribute
10 more broadly to psychological restoration and well-being (Ratcliffe, 2021). The present findings
11 are in line with the observation of reduced restorative effects for people with tinnitus and
12 sensorineural hearing loss compared to NH people when visiting urban parks (Payne, 2008a,b).
13 Still, these data should be considered with caution given the small number of NH and HI
14 individuals who participated in the present study (n=15 in each group), age mismatch between
15 the two groups (NH: 18-48 years vs. HI: 20-83 years) and use of single acoustic database
16 corresponding a temperate forest. For these reasons, further work is needed to replicate and
17 extend the present study to other cohorts of NH and HI listeners and terrestrial habitats, and
18 include simulations of crucial aspects of sensorineural hearing loss (reduced audibility, loudness
19 recruitment, reduced frequency selectivity) with NH listeners. In addition, it would be useful to
20 develop a dedicated questionnaire to assess the extent to which HI people are aware of this
21 degradation and how it affects their quality of life. Further work should also establish (i) the
22 extent to which sensorineural hearing loss alters the listening strategies of HI people, and (ii)
23 whether current hearing aids restore or degrade perception of natural soundscapes. Finally, more

1 applied research is needed to establish the extent to which hearing aids – and especially
2 nonlinear amplification and environment classification algorithms – restore or degrade accurate
3 perception of natural soundscapes and their variations.

4

5 More broadly, the present study is in line with previous attempts to better understand the
6 "relationship between the acoustic environments in which people live and their auditory needs in
7 these environments" (Gatehouse et al., 1999). This refers to the listening environments in which
8 humans live and work, the tasks to be performed in these environments and the importance of
9 these tasks in daily life, an idea they coined under the term "auditory ecology". The use of this
10 concept – although raising increasing interest in audiology – has been mostly restricted to the
11 case of urban settings (Keidser et al., 2020). Here we propose to apply it to study a different
12 issue, namely the auditory monitoring of natural scenes such as those encountered by normal-
13 hearing and hearing-impaired people living in rural areas or city dwellers who regularly visit
14 green spaces or national parks.

15

16 **4.5. CONCLUSIONS**

17 Natural soundscape discrimination was investigated for a group of listeners with sensorineural
18 hearing loss. The results showed that:

19 (1) Their capacity to discriminate natural soundscapes associated with changes in habitat,
20 season and period of the day was significantly poorer-than-normal. Still, this capacity was not
21 abolished, even for severe forms of hearing loss.

22 (2) The lower performance of hearing-impaired listeners was not related to age *per se*.

1 (3) At the group level, their lower performance could be partly accounted for by reduced
2 audibility as shown by the performance of NH listeners tested with spectrally-shaped stimuli
3 matching HI audiograms. Still, it was not significantly related to pure-tone audiometric
4 thresholds measured between 0.25 and 8 kHz.

5 Altogether, these results can be interpreted as evidence that individuals with sensorineural
6 hearing loss experience a significant deficit in their capacity to construct a normal representation
7 of natural environments. According to the present data, this decline in natural soundscape
8 perception may be attributed, at least partly, to reduced audibility and supra-threshold auditory
9 deficits. In particular, listening strategies may differ between NH and HI listeners. However,
10 ageing *per se* does not seem to impact the capacity to discriminate natural soundscapes.

11

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19 suggestions.

20

21 **DISCLOSURE STATEMENT**

22 The authors declare that they have no conflict of interest.

23

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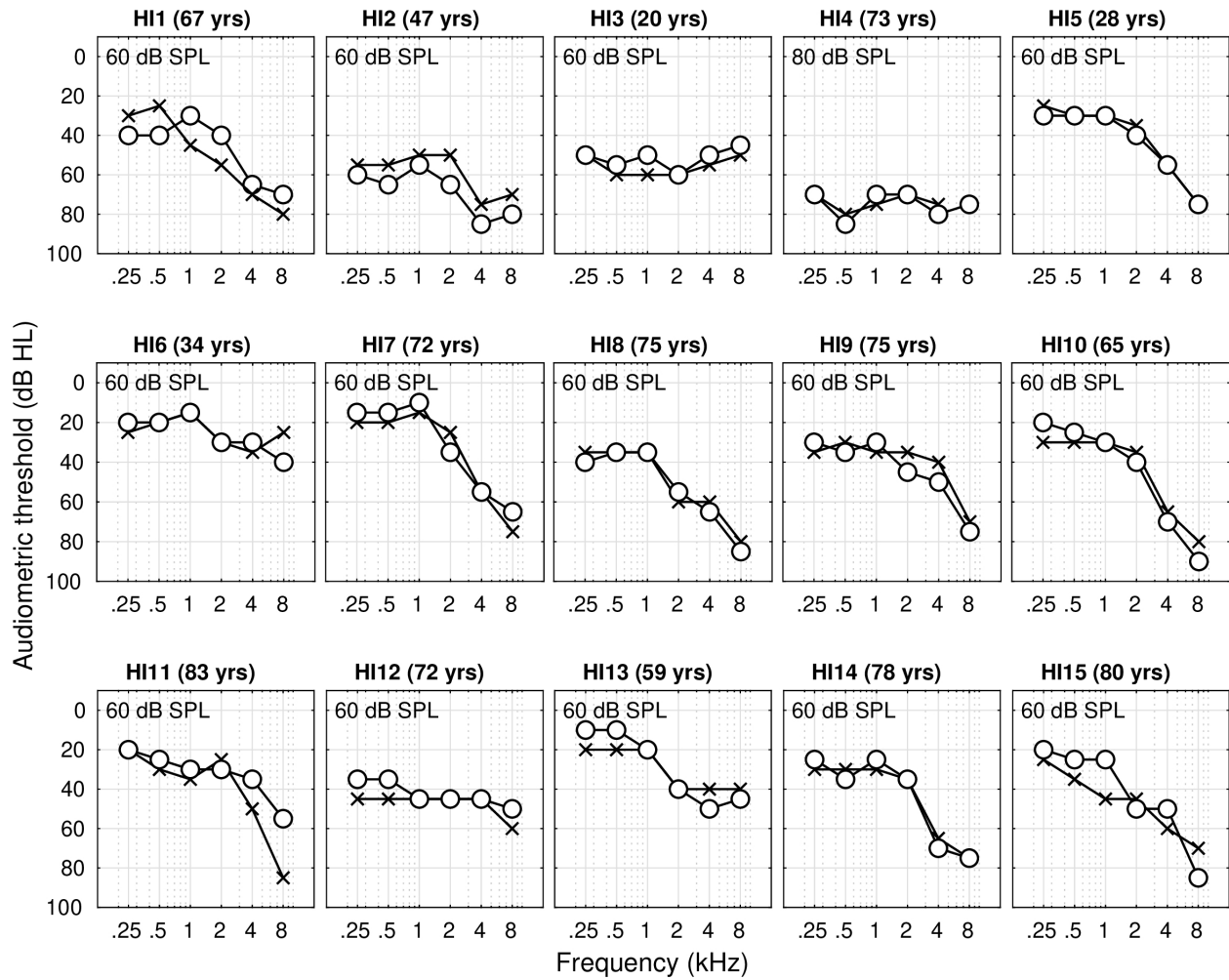
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27

Normal-hearing listeners					Hearing-impaired listeners				
Participant	Gender	Age	PTA	MF/HF PTA	Participant	Gender	Age	PTA	MF/HF PTA
NH6	M	36	8	5	HI6	F	34	25	32
NH13	M	27	1	-4	HI13	F	59	30	43
NH7	M	31	5	1	HI7	M	72	34	52
NH11	M	33	8	10	HI11	M	83	37	47
NH5	F	29	9	10	HI5	F	28	43	56
NH9	M	36	8	6	HI9	F	75	43	53
NH14	M	24	4	1	HI14	M	78	44	59
NH10	F	27	10	9	HI10	M	65	45	63
NH12	F	31	0	-4	HI12	F	72	45	48
NH15	F	18	7	4	HI15	F	80	45	60
NH1	F	37	6	6	HI1	F	67	49	63
NH8	M	25	7	8	HI8	F	75	52	68
NH3	F	23	6	1	HI3	F	20	54	53
NH2	M	48	15	11	HI2	F	47	64	71
NH4	F	29	9	4	HI4	M	73	75	74

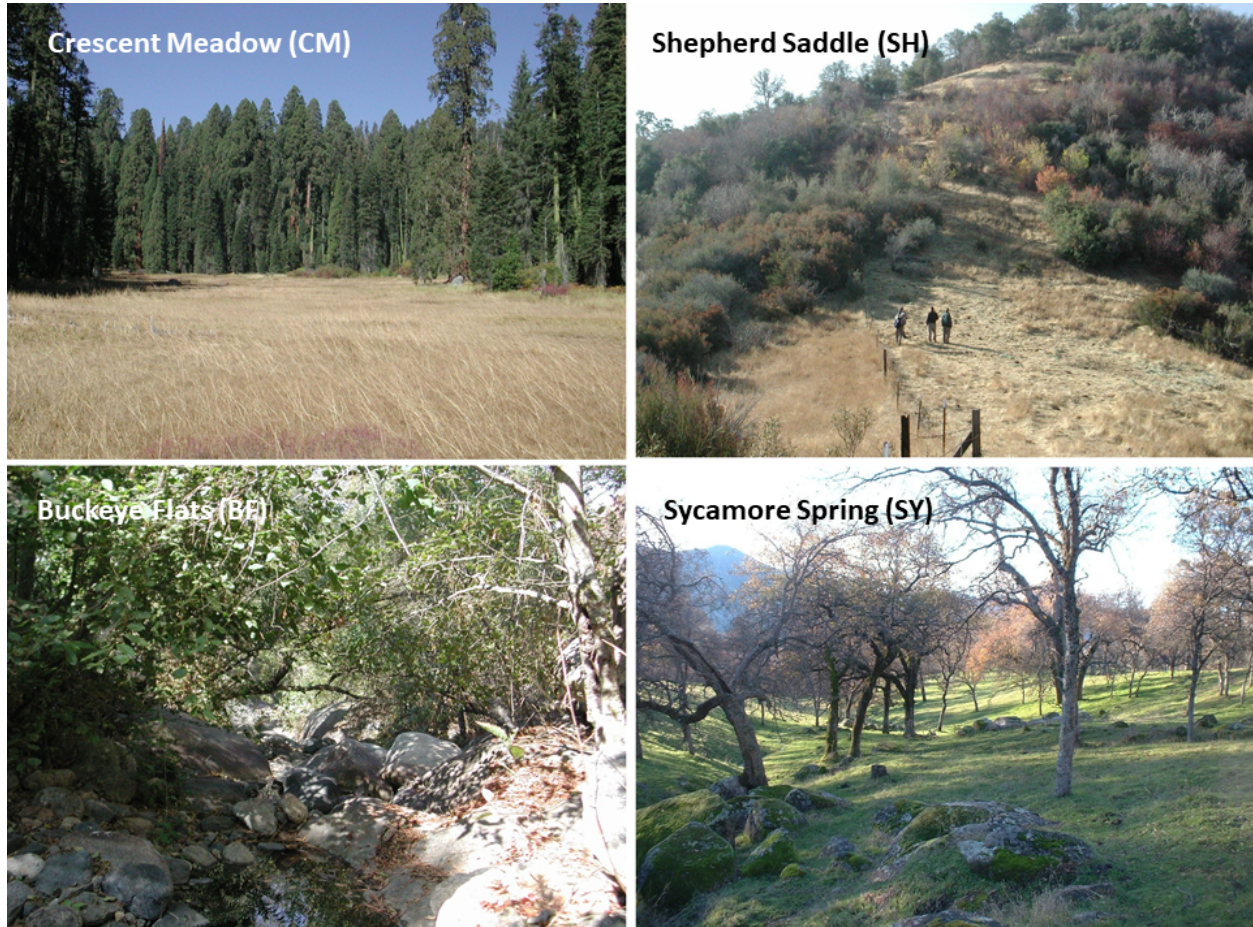
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2 **Table 1** Gender, age (in years), pure-tone average (PTA, dB HL) and mid/high-frequency PTA
3 (MF/HF-PTA, dB HL, mean at 2, 4 and 8 kHz) of the 15 NH listeners (left columns) and the 15
4 HI listeners (right columns).

NH listeners (SS condition)						Matched with
NH Participant	Level	Attenuation	Filtering	Cutoff	Slope	HI Participant
NH1	31	29	Lowpass	1	12	HI1
NH2	19	41	Lowpass	2	24	HI2
NH3	20	45	None	-	-	HI3
NH4	30	61	None	-	-	HI4
NH5	40	20	Lowpass	1	6	HI5
NH6	52	8	Lowpass	1	12	HI6
NH7	53	7	Lowpass	1	18	HI7
NH8	30	30	Lowpass	1	24	HI8
NH9	36	24	Lowpass	4	30	HI9
NH10	43	17	Lowpass	2	30	HI10
NH11	39	21	Lowpass	4	30	HI11
NH12	22	38	Lowpass	4	12	HI12
NH13	48	12	Lowpass	1	18	HI13
NH14	39	21	Lowpass	2	30	HI14
NH15	41	19	Lowpass	1	12	HI15

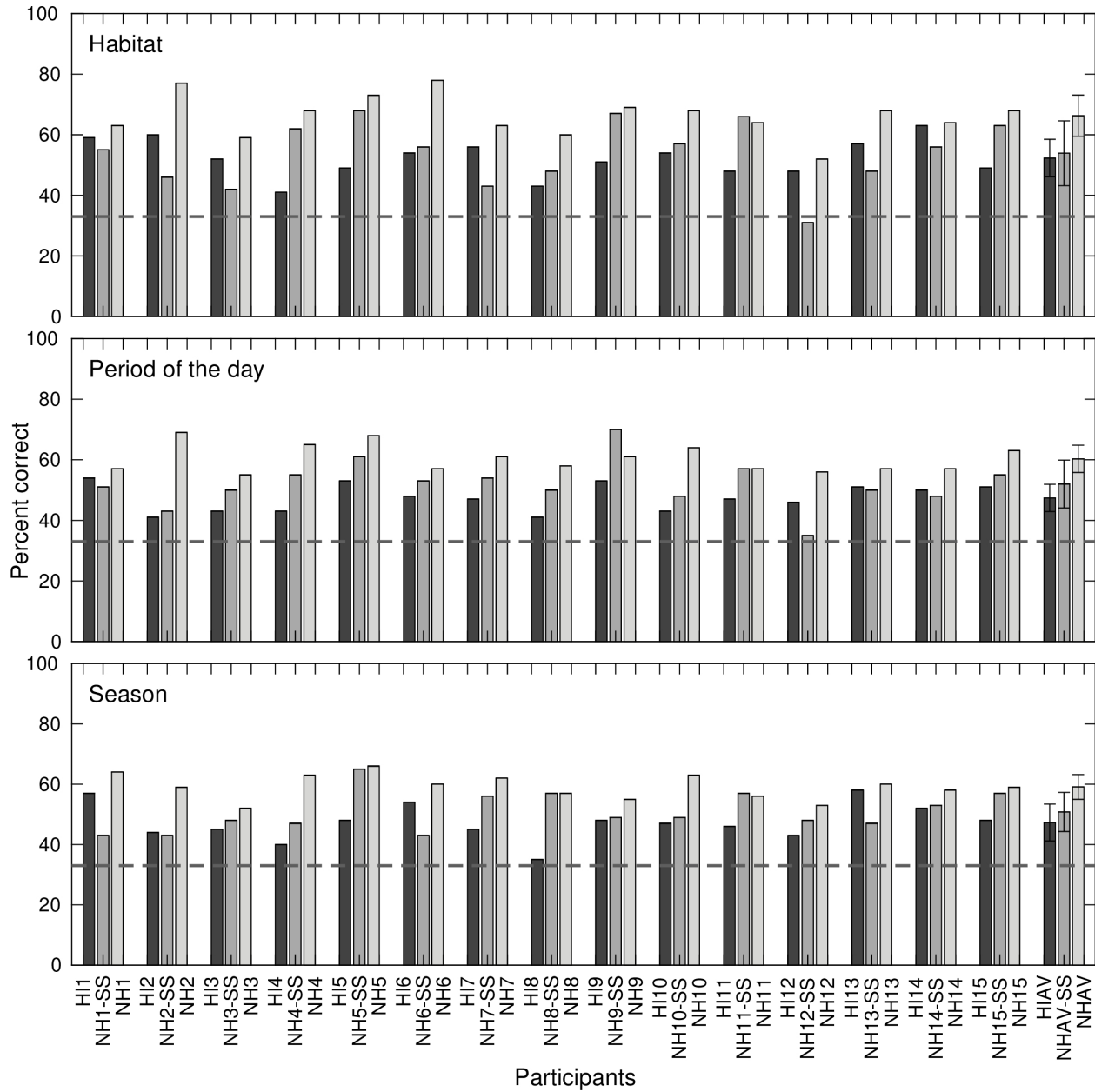
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2 **Table 2** Specifications of the final presentation level (jn dB), attenuation (in dB) and audio-
3 frequency filtering (no filtering or lowpass filtering [cutoff frequency (in kHz) and rolloff (in
4 dB/Oct)] used for each NH listener in the SS (Spectral Shaping) condition. Each NH is
5 audiometrically paired with a HI listener (rightmost column). For listeners NH3 and NH4
6 attenuation was adjusted manually until they could perform the task, so it was reduced by 5 and
7 11 dB, respectively.
8



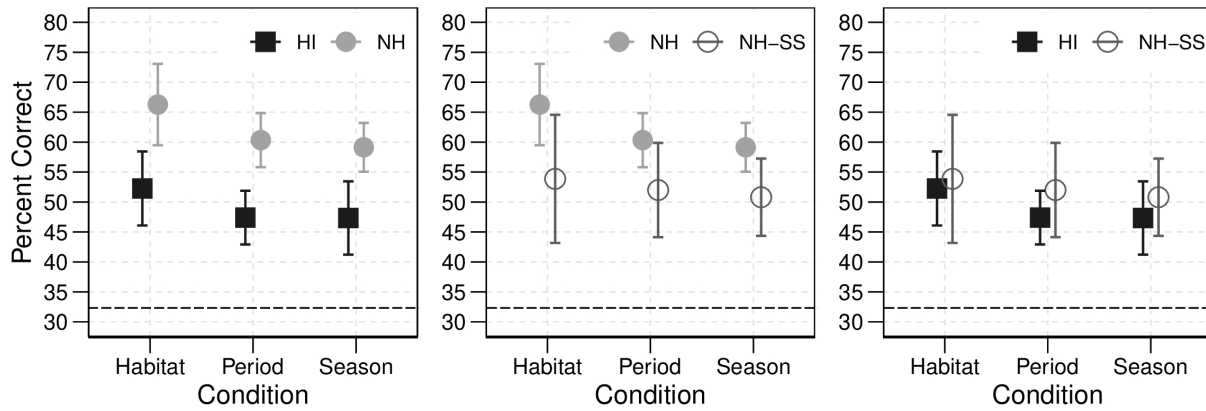
2 **Fig. 1** Individual audiometric thresholds (in dB HL) of the left (crosses) and right (circles) ears
 3 of the 15 HI listeners. Each panel shows the audiometric thresholds of a given HI listener. Age
 4 (in years) and presentation level (in dB SPL) are shown within each panel.
 5



2 **Fig. 2** The four areas within the Sequoia National Park (southern Sierra Nevada, California,
3 USA) selected for this study. Each one of these sites corresponds to a different habitat with a
4 particular combination of elevation and vegetation diversity: CM is a meadow surrounded by
5 sequoia trees; SH is a dry savannah chaparral with high winds; BF is a riparian area with a
6 relatively loud stream; and SY is a foothill site dominated by an oak savannah. The stimuli used
7 (1440 2-sec long acoustic samples for each site, 5760 total) were extracted from the 64 hours of
8 acoustic recordings collected by Krause *et al.* (2011) in the Sequoia National Park.



2 **Fig. 3** Individual and mean discrimination scores (in % correct) for HI listeners, NH listeners
 3 tested with spectrally-shaped stimuli (NH-SS), and NH listeners. The four age matched pairs
 4 correspond to participants number 2, 3, 5, and 6. Top panel: Habitat discrimination. Middle
 5 panel: Discrimination of period of the day. Bottom panel: Season discrimination. In each panel,
 6 rightmost bars show the average scores (AV). Error bars represent one standard deviation about
 7 the mean. The horizontal dashed line shows chance level (33% correct discrimination).



2 **Fig. 4** Mean discrimination scores (in % correct) for hearing impaired listeners (HI; black
 3 squares), normal hearing listeners (NH; grey circles), and normal hearing listeners tested with
 4 spectrally-shaped stimuli (NH-SS; open grey circles). Left panel: NH and HI listeners. Middle
 5 panel: NH and NH-SS listeners. Right panel: NH-SS and HI listeners. Error bars represent one
 6 standard deviation about the mean. The horizontal dashed line shows chance level (33% correct
 7 discrimination).