Hearing again with two ears: Recovery of spatial hearing after bilateral cochlear implantation

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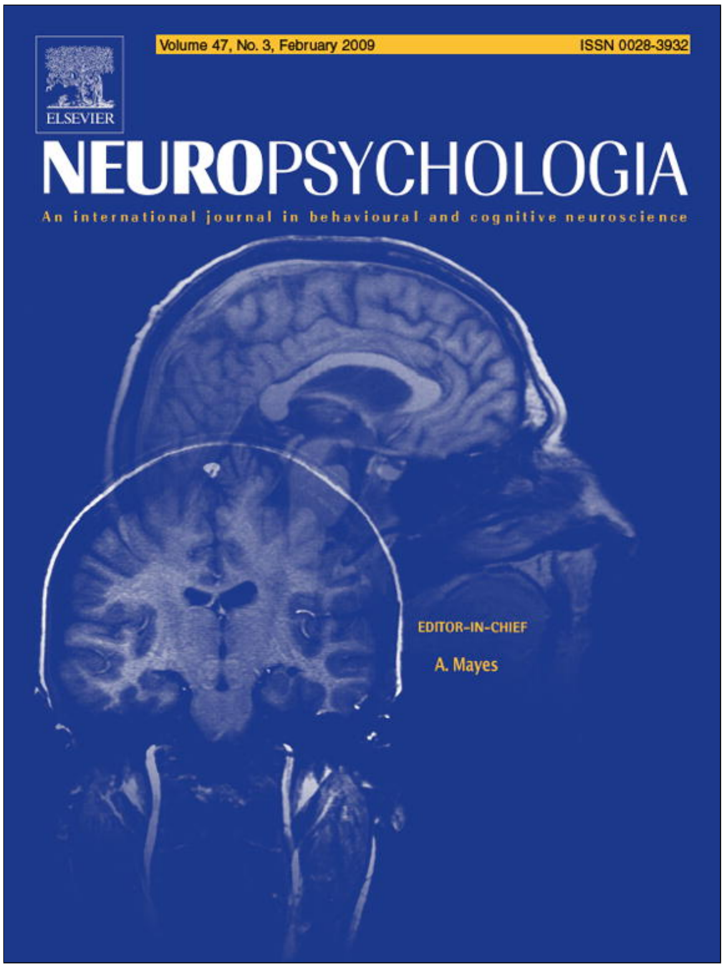
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Note

Hearing again with two ears: Recovery of spatial hearing after bilateral cochlear implantation

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ABSTRACT

Bilateral cochlear implants (CI) offer a unique opportunity for the study of spatial hearing plasticity in humans. Here we studied the recovery of spatial hearing in two sequential bilateral CI recipients, adopting a longitudinal approach. Each recipient was tested in a sound-source identification task shortly after bilateral activation and at 1, 6, and 12 months follow-up. The results show fast recovery (1 month from CI activation) in the recipient who had substantial experience with auditory cues in adulthood. By contrast, the bilateral CI recipient who developed profound deafness in childhood, regained spatial hearing abilities only 12 months after CI activation. These findings provide the first direct evidence that recovery of auditory spatial abilities in bilateral CI recipients can occur shortly after activation of the two devices. In addition, they suggest that previous auditory experience can constrain the time course of this recovery.

1. Introduction

Functional and neural reorganization after sensory deafferentation is a widely documented phenomenon (for recent reviews see Bavelier & Neville, 2002; Pascual-Leone, Amedi, Fregni, & Merabet, 2005). By contrast, much less is known about plasticity following sensory reafferentation (e.g., Giraud, Truy, & Frackowiak, 2001). A unique opportunity for the study of sensory reafferentation is offered by cochlear implants (CI). CIs are neuroprosthetic devices routinely adopted in the clinical practice that restore functional hearing through direct electrical stimulation of the auditory nerve. Although the vast majority of CIs are implanted monaurally, an increasing number of recipients now receive bilateral CIs, thus giving the opportunity to examine the recovery of binaural spatial hearing in humans.

Several studies have documented a substantial recovery of spatial hearing in bilateral CI users (e.g., Neuman, Haravon, Sislian, & Waltzman, 2007; Schoen, Mueller, Helms, & Nopp, 2005; Van Hoesel & Tyler, 2003). However, a number of important issues remain to be addressed. First, the earliest recovery of spatial hearing in bilateral CI recipients has been documented to appear 3 months after implant activation (Nopp, Schleich, & O'Hease, 2004; Verschuur, Lutman, Ramsden, Greenham, & O'Driscoll, 2005), suggesting that a relatively long period of adaptation to binaural hearing is necessary before spatial hearing abilities can be restored. These previous studies, however, adopted a transversal approach (i.e., different recipients tested at different intervals from activation), lacking to investigate the exact time course of binaural hearing recovery within each single recipient. Second, the role of previous auditory experience in modulating recovery of spatial hearing is still an open issue. Although some investigators have proposed that the rapidity and efficacy of recovery may be closely linked to the amount of auditory experience acquired by the recipient before deafness-onset (Grantham, Ashmead, Ricketts, Labadie, & Haynes, 2007; Litovsky et al., 2004), to date there has been no systematic study addressing the role of previous auditory experience on spatial hearing recovery. Finally, a third unexplored issue concerns the interplay between monaural and binaural sound localisation abilities during binaural recovery. Particularly when the two CIs are implanted sequentially (i.e., the second CI is implanted after several months or years of experience with the first monaural implant; e.g., Nopp et al., 2004; Verschuur et al., 2005), it remains unclear to what extent any previously developed

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plasticity to monaural hearing might interact with the new inputs arising from binaural implantation.

In the current study, we had the opportunity to test two sequential bilateral CI recipients (S.P. and P.A.), with comparable characteristics with respect to CI surgery (age at first and second implant and years of experience using the first monaural implant), but substantially different clinical histories with respect to their exposure to auditory cues. S.P. became deaf late in life when aged 39, whereas P.A. became deaf during childhood when aged 4. Both recipients were tested in a sound-source identification task, with their first CI active (monaural testing condition) or with both CIs active (binaural testing condition). S.P. and P.A. were tested on the very first day of the second CI activation, and in several follow-up sessions within the first 12 months from activation. The longitudinal approach adopted here for the first time allowed the assessment of both the exact time course of binaural recovery after bilateral CI and the potential interplay between monaural and binaural hearing strategies.

2. Methods

2.1. Participants

S.P. is a 46-year-old man, who became progressively deaf at around 30 years of age due to otoschlerosis. He wore acoustic external prosthesis until he became profoundly deaf (>90 dB) when aged 39. He received his first implant in the right ear when aged 40, and the second implant in the left ear when aged 46 (MED-EL Pulsar with FSP strategy in both ears).

P.A. became progressively deaf at around 4 years of age for unknown causes. He used acoustic prosthesis from the age of 6. However, when tested with the prosthesis

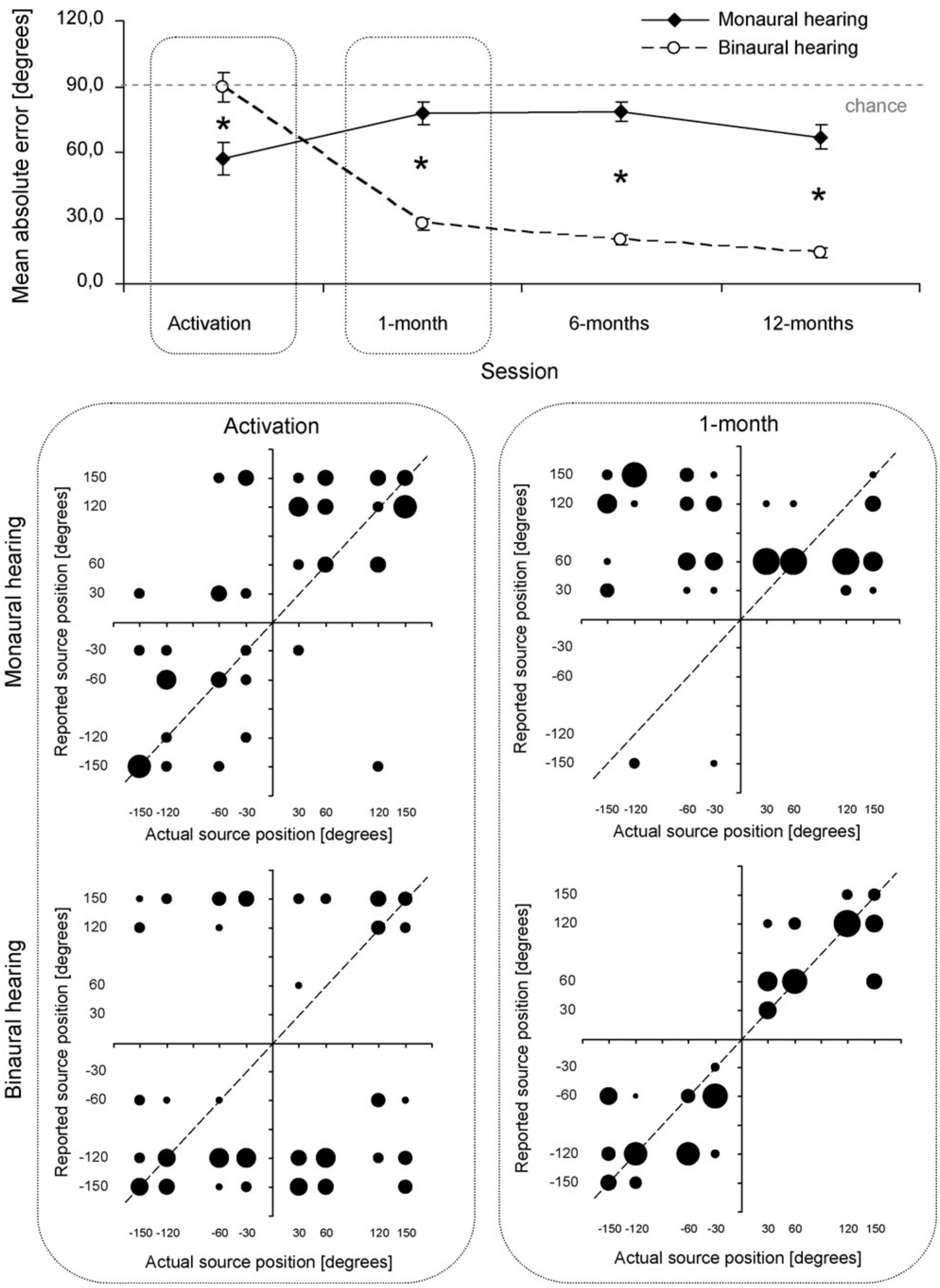

Fig. 1. Mean absolute error in the four testing sessions for recipient S.P.; error bars indicate the standard error of the mean; asterisks indicate significant differences between monaural and binaural performance. Bubble plots illustrate distribution of responses during monaural and binaural testing, in the day of bilateral activation and in the 1-month follow-up (i.e., the session in which the first improvement of binaural spatial hearing emerged for this recipient).

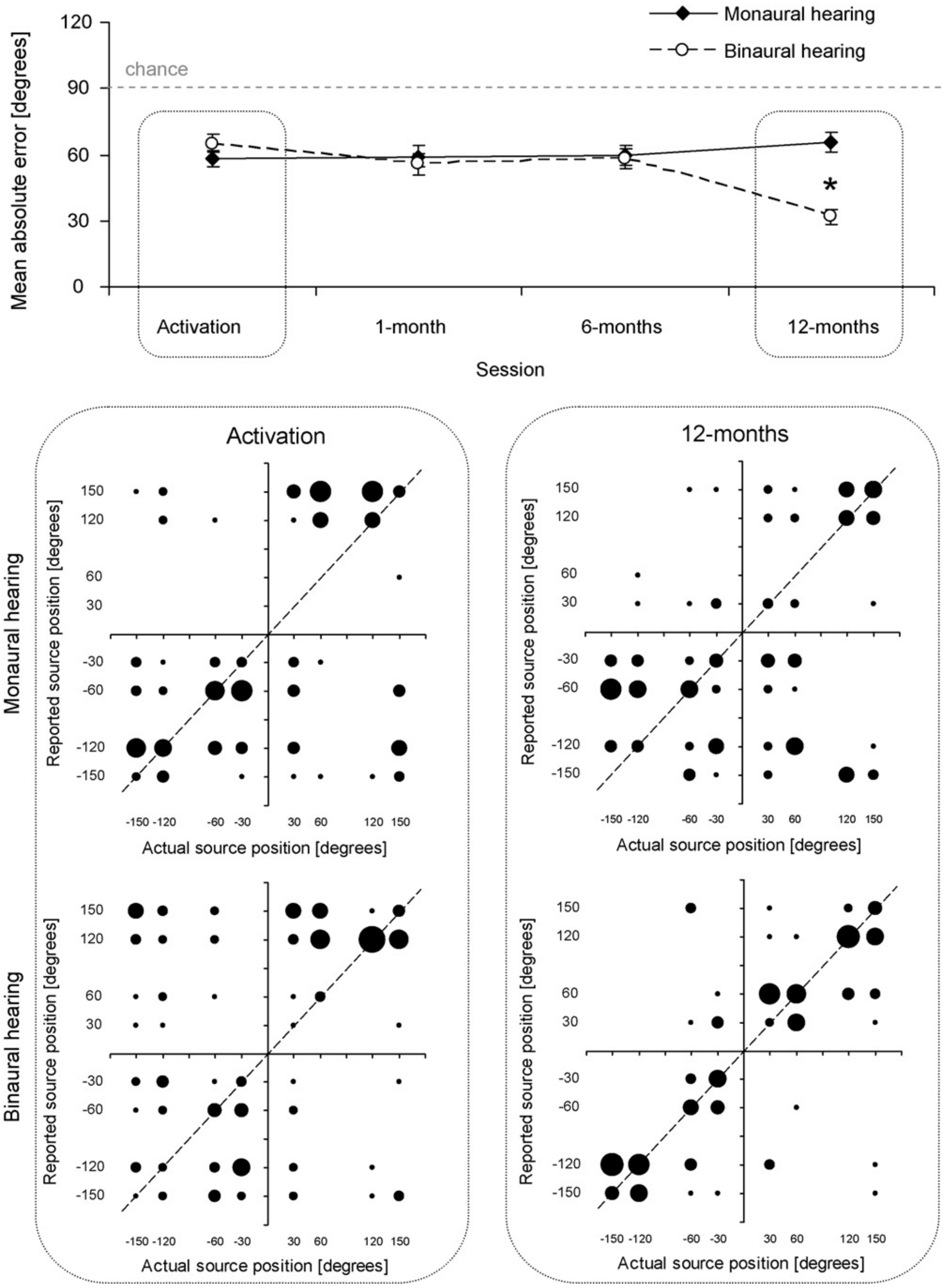

Fig. 2. Mean absolute error in the four testing sessions for recipient P.A.; error bars indicate the standard error of the mean; asterisks indicate significant differences between monaural and binaural performance. Bubble plots illustrate distribution of responses during monaural and binaural testing, in the day of bilateral activation and in the 12-month follow-up (i.e., the session in which the first improvement of binaural spatial hearing emerged for this recipient).

before the first CI surgery, his auditory abilities for verbal materials were rather poor even at maximal stimulation intensities. He received his first implant in the left ear when aged 36, and the second implant in the right ear when aged 40 (Cochlear Freedom Contour Advance with ACE strategy in the left ear, Cochlear Nucleus 24 Contour with ACE strategy in the right ear).

The bilateral audiogram threshold for case P.A. was 25 dB HL for all frequencies between 250 Hz and 4 kHz, when measured 1 month after bilateral activation and 30 dB HL when measured 12 months from activation. The bilateral audiogram threshold for case S.P. for the same frequency range was 35 dB HL when measured 1 month after bilateral activation.

2.2. *Apparatus, stimuli and procedure*

The two recipients performed the sound-source identification test in a silent room. The set-up consisted of eight loudspeakers, positioned in a circle (radius 60 cm) around the participant who sat in the centre. With respect to the straight-ahead position (0°), loudspeakers were positioned at +30°, +60°, +120° and +150° on the right side of the participant, and at −30°, −60°, −120° and −150° on the left side of the participant. Stimuli were generated using Matlab and consisted of a sequence of four 20 ms noise bursts, separated by 80 ms intervals (overall stimulus duration was 400 ms). Each stimulus was randomly delivered six times from each loudspeaker, in three separated blocks (48 trials per block; 144 fully randomised presentations in total). We also randomly varied the intensity level of each speaker (±4 dB) so that minimal intensity differences between speakers could not aid source identification. In addition, an acoustically transparent close weave cloth, specifically designed for mounting on loudspeaker grilles when cut smaller than the complete sheet used here (Model: KS50E, Maplin, UK), covered all frontal loudspeakers to avoid visual cues to localisation.

Participants were asked to verbally identify the loudspeaker from which they considered the sound to have originated. To provide their answer, participants were given a diagram with the representation of all possible loudspeakers' spatial positions. The experimenter arbitrarily timed stimulus presentation by pressing a button on the computer keyboard (approximately 1 stimulus every 3 s). The two recipients performed the sound-source identification test, both monaurally and binaurally, in 4 separate experimental sessions: immediately after bilateral activation, and at 1, 6 and 12 months follow-up. Note that monaural testing was always performed with the first implanted device for each recipient (i.e., right CI for S.P. and left CI for P.A.). Within each session the order of monaural and binaural blocks was counterbalanced and the participant rested between blocks. No repeats were allowed and no feedback was given. Each session took approximately 45 min to complete.

3. Results

3.1. Recipient S.P.

The performance of S.P. (late deafness-onset) is illustrated in Fig. 1. When S.P. was tested shortly after activation of the second implant, he performed worse with binaural than monaural hearing. Mean absolute error in this first session was 57° (S.E. = 7) with monaural hearing, and 90° (S.E. = 7) with binaural hearing ($t(116) = 3.3$, $p < 0.001$; chance performance with this set-up was 90° error). On most monaural trials, S.P. was able to discriminate the location of stimuli in azimuth (net azimuth error computed by collapsing front and back locations was 24°, S.E. = 4). This value is lower than the minimal spatial separation between speakers (i.e., 30°).

Strikingly, S.P.'s performance with binaural hearing improved substantially already in the first follow-up session, 1 month after activation of the second implant (see Fig. 2a). Mean absolute error in the binaural testing condition was reduced to 27° (S.E. = 3; $t(124) = 8.9$, $p < 0.0001$, with respect to binaural performance in the activation session). By contrast, his monaural localisation ability dropped to 78° overall (S.E. = 5) with respect to the activation session ($t(94) = 2.3$, $p = 0.02$). S.P. localised almost all sounds to the right hemispace (i.e., the side of the first monaural implant; net azimuth error was 51°, S.E. = 4; see monaural hearing bubble plot at 1 month in Fig. 1).

This improved performance with binaural over monaural hearing was confirmed also at the 6 and 12 months follow-up sessions. In fact, S.P.'s binaural localisation improved even further in the 6 months follow-up (mean absolute error = 20°, S.E. = 3; $t(286) = 2.0$, $p = 0.05$; net azimuth error was 8°, S.E. = 1), and in the 12 months follow-up (mean absolute error = 14°, S.E. = 2; $t(277) = 1.9$, $p = 0.03$, one-tail; net azimuth error was 7°, S.E. = 1). By contrast, monaural performance remained stable in both sessions (6 months: mean absolute error = 79°, S.E. = 4; 12 months: mean absolute error = 79°, S.E. = 4).

3.2. Recipient P.A.

The performance of P.A. (early deafness-onset) is illustrated in Fig. 2. When P.A. was tested shortly after activation of the second implant, he showed comparable performance with both binaural and monaural hearing. Mean absolute error in the first session was 58° (S.E. = 4) for the monaural testing condition, and 65° (S.E. = 4) for the binaural testing condition ($t(283) = 1.2$, $p = 0.2$); significantly below chance for both monaural ($t(143) = 8.1$, $p < 0.0001$) and binaural hearing ($t(143) = 5.7$, $p < 0.0001$). His error in azimuth was 32° (S.E. = 3) with both hearing conditions.

Critically, however, no modulation of performance emerged for P.A. in the 1 and 6 months follow-up sessions. Binaural hearing abilities remained stable in these two follow-up sessions (1 month: mean absolute error = 56°, S.E. = 5; 6 months: mean absolute error = 58°, S.E. = 4). Similarly, monaural hearing abilities were approximately identical across sessions (1 month: mean absolute error = 59°, S.E. = 5; 6 months: mean absolute error = 60°, S.E. = 5).

A significant change in binaural abilities emerged instead 12 months after activation. Mean absolute error in the binaural condition improved to 32° (S.E. = 3; $t(143) = 5.01$, $p < 0.0001$). Note that this is comparable to the absolute mean error showed by recipient S.P. in the 1 month follow-up session.

4. Discussion

The current study provides the first longitudinal investigation of spatial hearing recovery in bilateral CI recipients, examined here from the moment of bilateral implant activation and in several follow-up sessions within the first 12 months of regained binaural hearing. Our findings demonstrate that recovery of spatial hearing can emerge already 1 month from bilateral CI activation, suggesting the possibility of fast plastic changes in spatial hearing after bilateral reafferentation of the auditory pathways. This is clearly illustrated by the performance of recipient S.P., who acquired profound deafness in adulthood. Despite a poor bilateral performance immediately after activation, S.P. shows substantial recovery of spatial hearing abilities with two active implants already in the first follow-up session (1 month), and improved even further at the 6 and 12 months follow-up. Intriguingly, this fast recovery of binaural spatial hearing appears to have occurred at the expenses of the pre-existing monaural abilities, suggesting a possible interplay between monaural and binaural sound localisation strategies in sequential CIs.

Fast plastic changes of spatial hearing have been previously documented in individuals with normal hearing abilities whose spectral-shape cues were perturbed using binaural (Hofman, Van Riswick, & Van Opstal, 1998) or monaural molds on the participant's pinnae (Van Wanrooij & Van Opstal, 2005). Listeners tested with these paradigms relearned sound localisation within a few weeks from ear molding. In addition, immediately after removal of the molds, all participants regained a level of sound localisation accuracy comparable to that recorded at the beginning of the experiment several weeks earlier (Hofman et al., 1998). Similarly, in the classic studies by Knudsen and colleagues (1984), young barn owls that were monaurally occluded after having developed adult binaural cues, relearned to localize normally with the two ears after the monaural earplug removal. This suggests that recovery of well-acquired mappings between auditory cues and space can occur very fast even after substantial intervening changes affecting auditory perception, such as ear molding (Van Wanrooij & Van Opstal, 2005), monaural ear occlusion (Knudsen, Knudsen, & Esterly, 1984) or a period of profound deafness as reported here.

In agreement with this notion that fast recovery of spatial hearing may be closely dependent upon well-acquired experience with auditory cues, the current study reveals that recovery of auditory spatial abilities is substantially slower when previous experience with auditory cues has been limited. This is clearly illustrated by the performance of recipient P.A., who acquired profound deafness in childhood. Unlike recipient S.P., recipient P.A. did not show an improvement of binaural abilities until 12 months from bilateral CI activation. The striking difference between time of recovery of our two bilateral CI recipients clearly suggests that fast recovery may be constrained by the recipient's previous experience with auditory localisation cues. Intriguingly, the current findings indicate that despite sound localisation maturity was likely impaired (if not entirely compromised) in P.A., it did not prevent progressive relearning of systematic mappings between auditory cues and space. Thus, despite complex aspects of hearing, such as sound localisation, achieve maturity during the years of adolescence (Moore, 2002), the brain appears nonetheless capable of learning how to interpret auditory cues in adulthood as well (see also Hofman et al., 1998; King et al., 2000, 2001).

Which auditory cues could have supported the recovery of spatial hearing abilities of our two recipients in the binaural hearing condition? Monaural spectral cues from each of the two ears unlikely account for the improved localisation performance, because these cues minimally contribute to localisation in azimuth in normal hearing individuals (e.g., Van Wanrooij & Van Opstal, 2004, 2005) and are substantially limited with multi-electrode implants. Instead, we cannot exclude that monaural cues related to the head-shadow effect (HSE; systematic changes in the proximal stimulus intensity at each ear as a function of the azimuthal location of the sound-source; Van Wanrooij & Van Opstal, 2004) could have played some role, due to the limited range of sound intensity variations in our study (± 4 dB, while HSE variations are in the range of ±10 dB). However, a number of systematic studies addressing specifically the contribution of different auditory cues in bilateral recipients suggest that binaural cues may indeed return available when two devices are active. In particular, several recent studies point to a key role of interaural level differences (instead of interaural time differences) in regained localisation abilities of bilateral CI recipients (Grantham, Ashmead, Ricketts, Haynes, & Labadie, 2008; Seeber & Fastl, 2007).

In conclusion, the results of the present study demonstrate that recovery of spatial hearing with bilateral CI can emerge in the shortest period after reafferentation, at least for the recipient who had the most extensive experience with auditory cues. Intriguingly, this binaural recovery in S.P. appears to have occurred at the expenses of his monaural abilities, as if 1 month of binaural hearing overcame the experience acquired in 5 years of monaural hearing. This fast recovery is compatible with re-programming of the auditory spatial mappings that S.P. acquired before deafness-onset. By contrast, the longer time-course of recovery of case P.A. could reflect the gradual process of learning auditory spatial mappings which were not fully acquired before deafness-onset.

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