

# 1 **Research Report**

## 2 3 **Adaptive benefit of cross-modal plasticity following** 4 **cochlear implantation in deaf adults**

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### 29 30 **Classification**

31 Biological Sciences: Neuroscience

### 32 33 **Keywords**

34 Cochlear implantation; Cross-modal plasticity; Functional near-infrared spectroscopy;  
35 Superior temporal cortex; Visual speech

## 37 **Abstract**

38 It has been suggested that visual language is maladaptive for hearing restoration with a cochlear  
39 implant (CI) due to cross-modal recruitment of auditory brain regions. Rehabilitative  
40 guidelines therefore discourage the use of visual language. However, neuroscientific  
41 understanding of cross-modal plasticity following cochlear implantation has been restricted  
42 due to incompatibility between established neuroimaging techniques and the surgically  
43 implanted electronic and magnetic components of the CI. As a solution to this problem, here  
44 we employed functional near-infrared spectroscopy (fNIRS), a non-invasive optical  
45 neuroimaging method that is fully compatible with a CI and safe for repeated testing. The aim  
46 of this study was to examine cross-modal activation of auditory brain regions by visual speech  
47 from before to after implantation and its relation to CI success. Using fNIRS, we examined  
48 activation of superior temporal cortex to visual speech in the same profoundly deaf adults both  
49 before and six months after implantation. Patients' ability to understand auditory speech with  
50 their CI was also measured following six months of CI use. Contrary to existing theory, the  
51 results demonstrate that increased cross-modal activation of auditory brain regions by visual  
52 speech from before to after implantation is associated with better speech understanding with a  
53 CI. Furthermore, activation of auditory cortex by visual and auditory speech developed in  
54 synchrony after implantation. Together these findings suggest that cross-modal plasticity by  
55 visual speech does not exert previously assumed maladaptive effects on CI success, but instead  
56 provides adaptive benefits to the restoration of hearing after implantation through an audio-  
57 visual mechanism.

58

## 59 **Significance statement**

60 Following sensory deprivation, the sensory brain regions can become colonized by the other  
61 intact sensory modalities. In deaf individuals, evidence suggests that visual language recruits  
62 auditory brain regions and may limit hearing restoration with a cochlear implant. This  
63 suggestion underpins current rehabilitative recommendations that deaf individuals undergoing  
64 cochlear implantation should avoid using visual language. However, here we show the  
65 opposite: recruitment of auditory brain regions by visual speech after implantation is associated  
66 with better speech understanding with a cochlear implant. This suggests adaptive benefits of  
67 visual communication, as visual speech may serve to optimise, rather than hinder, restoration  
68 of hearing following implantation. These findings have implications for both neuroscientific  
69 theory and the clinical rehabilitation of cochlear implant patients worldwide.

70 \body

## 71 **Introduction**

72 A cochlear implant (CI) is an auditory prosthesis that provides a sensation of hearing to deaf  
73 individuals by electrically stimulating spiral ganglion cells of the auditory nerve. In deaf  
74 individuals, auditory regions of the brain that usually process sound can become responsive to  
75 visual stimuli (1). This cross-modal plasticity within auditory cortex can provide adaptive  
76 benefits such as superior visual localisation and motion detection abilities (2). On the other  
77 hand, cross-modal plasticity can limit a deaf individual's ability to understand speech after their  
78 hearing is restored with a cochlear implant (3, 4). Therefore, it is assumed that this maladaptive  
79 cross-modal activation of auditory brain regions must decrease following cochlear implantation  
80 for speech understanding to be restored successfully (4). However, in recent years, this  
81 traditional dichotomous stance on the adaptive effects of cross-modal plasticity during sensory  
82 deprivation versus its maladaptive effects during sensory restoration has been highlighted as  
83 too simplistic (5). For instance, it has been proposed that receiving visual linguistic input in the  
84 absence of auditory input may not necessarily limit the recovery of auditory function following  
85 implantation, but instead could promote and maintain typical functioning of language  
86 networks, which could thus provide benefits for future CI outcome (5-7). However, these  
87 remain speculations as little empirical evidence exists regarding how cross-modal activation of  
88 auditory brain regions by visual speech (lip-reading) affects CI success (6, 7).

89

90 Existing evidence from a PET study in adult CI users showed that greater activation of auditory  
91 brain regions during lip-reading predicted poorer speech understanding abilities with a CI (8),  
92 and that this activity reduced from an earlier to a later stage of CI rehabilitation (9).  
93 Subsequently, it has been assumed that activation of auditory cortex by visual language can  
94 limit its capacity for auditory processing (3), and that a reduction in cross-modal activation of  
95 auditory cortex to visual speech after implantation may be crucial for successful hearing  
96 restoration (9). Such assumptions have led to clinical recommendations for deaf individuals  
97 undergoing cochlear implantation to avoid the use of visual language in order to maintain the  
98 ability of auditory brain regions to process auditory speech, and thereby optimise CI success.  
99 However, these assumptions are currently unsubstantiated (6): how cross-modal activation of  
100 auditory brain regions by visual speech changes from pre- to post-implantation, and how this  
101 relates to the ability to understand speech with a CI, has yet to be investigated. Furthermore,

102 the relationship between this post-implant cortical plasticity within auditory brain regions and  
103 the ability of these regions to respond auditory speech stimulation remains unexplored.

104

105 Pre-operative brain imaging of cochlear implant users is possible using techniques such as  
106 fMRI, which has been utilised to understand neural mechanisms that may underlie functional  
107 CI outcomes. For instance, maintenance of ‘typical’ phonological processing pathways in post-  
108 linguually deaf CI candidates, as revealed by a written word rhyming task performed prior to  
109 implantation, has been linked to better future CI outcome (10). However, since CI devices are  
110 generally incompatible with established neuroimaging techniques including fMRI, the ability  
111 to study pre- to post-implant cross-modal plasticity underlying hearing restoration with a CI  
112 has been severely limited (7). Here, we overcame these technical challenges by using an  
113 emerging optical technique, functional near-infrared spectroscopy (fNIRS), which offers full  
114 compatibility with CI devices (11) and is safe for repeated testing. This enabled us to directly  
115 examine changes in cross-modal activation of auditory brain regions by visual speech from  
116 before to after cochlear implantation, and its relation to CI success.

117

118 In line with the traditional dichotomous view of cross-modal plasticity and the available  
119 evidence, we hypothesised that a decrease in cross-modal activation of auditory brain regions  
120 by visual speech after implantation would be linked to better auditory speech understanding  
121 with a cochlear implant. Secondly, we investigated whether the ability of auditory brain regions  
122 to respond to sound following implantation depended on a reduction in cross-modal activation  
123 of these same regions by visual speech. We hypothesised that a decrease in cortical activation  
124 to visual speech after implantation would be linked to an increase in activation to auditory  
125 speech.

126

## 127 **Results**

128 Cross-modal activation of auditory brain regions during a visual speech task (lip-reading) was  
129 measured in 15 profoundly deaf individuals before cochlear implantation (T0) and 6 months  
130 after cochlear implantation (T1). Fig. 1 displays the aggregate sensitivity profiles for our  
131 regions of interest (ROIs), illustrating the regions of bilateral STC to which our measurements  
132 were theoretically sensitive.

133

134 For each individual, we first examined how cross-modal activation of auditory brain regions  
135 by visual speech changed from pre- to post-implantation. The direction and magnitude of  
136 change in cross-modal activation varied across the group: nine CI users displayed a decrease  
137 in activation, while the remaining six displayed an increase. The change in cross-modal  
138 activation was negatively correlated with the duration of bilateral hearing loss ( $r = -.58, p <$   
139  $.05$ , two-tailed; Fig. S1), with more recently deafened individuals tending to show an increase  
140 in cross-modal activation from pre- to post-implantation, and individuals with a longer duration  
141 of deafness tending to show a decrease. This suggests that an individual's clinical history of  
142 deafness may influence how the brain adapts following cochlear implantation. Perhaps  
143 unsurprisingly given this level of individual variability, there was no significant change in  
144 bilateral STC activation to visual speech at the group level from pre- to post-implantation (Fig.  
145 2A).

146

147 Linear mixed model analysis of the data show that: 1) there was no significant change in  
148 bilateral STC activation to visual speech over time across both CI users and NH controls (no  
149 main effect of time;  $F_{1,28.88} = 1.90, p = 0.18$ ; Fig. 2A), 2) there was no significant difference in  
150 cortical activation between CI users and NH controls across time points (no main effect of  
151 group;  $F_{1,34.79} = 0.98, p = 0.33$ ), and 3) changes in activation to visual speech over time did not  
152 differ between the two groups (no group – time interaction;  $F_{1,28.88} = 0.69, p = 0.41$ ).

153

154 A significant reduction in cross-modal activation to visual speech has previously been  
155 documented from approximately one week to eight months post-CI within anterior portions of  
156 the right superior temporal sulcus (9). Thus, we next examined changes in the amplitude of  
157 cross-modal activation to visual speech within the left and the right STC separately. While  
158 there was no significant change in cross-modal activation of the left STC from pre- to post-  
159 implantation (no main effect of time;  $F_{1,31.07} = 0.09, p = 0.76$ ; Fig. 2B), a significant change in  
160 cross-modal activation over time was indeed observed within the right STC (main effect of  
161 time;  $F_{1,30.01} = 6.47, p < .05$ ; Fig. 2C). This indicates that the amplitude of cross-modal activation  
162 to visual speech within right STC decreased significantly over time when assessed across both  
163 groups combined.

164

165 Data pertaining to changes over time in activation of auditory brain regions by visual speech  
166 are not available from existing studies for both CI users and NH control subjects (9). We  
167 therefore asked whether the observed change over time in right STC activation to visual speech

168 differed between CI users and NH controls. The analysis shows that pre- to post-CI changes in  
169 right STC activation did not significantly differ between the two groups (no significant main  
170 effect of group;  $F_{1,27.18} = 1.09$ ,  $p = 0.31$ , nor a group – time interaction;  $F_{1,30.01} = 0.49$ ,  $p = 0.49$ ).  
171 The absence of a significant group – time interaction demonstrates that the observed change in  
172 activation of right STC to visual speech over time was not specific to the CI group, and so  
173 cannot be attributed to the implantation process. However, the test-retest reliability of fNIRS  
174 responses to visual speech has been shown to be relatively poor over a retest interval of 3  
175 months, particularly in the right hemisphere (12). Therefore, it is possible that modest test-  
176 retest reliability prevented us from detecting a group–time interaction effect.

177

178 Auditory speech understanding six months after cochlear implantation ranged from 1 to 100  
179 %-correct, with a mean performance of 71 %-correct ( $SD = 33.2$ ). The large range of CI  
180 outcomes that we observed, as well as the mean performance, are consistent with previous  
181 reports from large-scale, international studies (13-15), indicating that the CI outcomes observed  
182 in the present study may be considered representative of the wider CI population.

183

184 To identify whether a reduction in cross-modal activation of auditory brain regions by visual  
185 speech was necessary for a successful outcome following cochlear implantation, we performed  
186 a within-subject analysis to examine the relationship between change in STC activation from  
187 pre- to post-implantation and speech understanding with the CI. There was a strong positive  
188 correlation between change in bilateral STC activation to visual speech and speech  
189 understanding ( $r = .77$ ,  $p < .01$ , two-tailed; Fig. 3). Separate correlation analysis of the left and  
190 right STC confirmed that this relationship was not driven predominantly by one cerebral  
191 hemisphere (left STC:  $r = .63$ ,  $p < .05$ ; right STC:  $r = .73$ ,  $p < .01$ , both two-tailed; Fig. S2A  
192 and S2B respectively). Thus, contrary to expectations we found that the best performing CI  
193 users showed an increase in cross-modal activation by visual speech from pre- to post-  
194 implantation, while the poorest performing CI users showed a reduction in cross-modal  
195 activation over time. Since the change in bilateral STC activation to visual speech was  
196 associated with the duration of deafness (see Fig. S1), we also examined the relationship  
197 between cross-modal plasticity and CI outcome while controlling for duration of deafness.  
198 Partial correlation analysis indicated that the observed strong positive correlation between  
199 change in bilateral STC activation to visual speech from pre- to post-implantation and speech  
200 understanding with a CI remained after controlling for the effect of duration of deafness ( $r =$   
201  $.70$ ,  $p < .01$ , two-tailed).

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It has been assumed that visual language may compromise the ability of auditory brain regions to respond to sound after implantation (3, 16), and that maladaptive cross-modal plasticity must be reversed for CI success (4). In order to explore the mechanisms underlying hearing restoration, we examined whether an increase in responsiveness of auditory brain regions to auditory speech stimulation after implantation was dependent on a decrease in cross-modal activation to visual speech. Contrary to expectations, we found a positive correlation between change in bilateral STC activation to auditory speech and change in cross-modal activation to visual speech from T0 to T1 ( $r = .51, p < .05$ , two-tailed; Fig. 4). This relationship between the auditory and visual modality did not exist in the NH control group ( $r = .09, p = .74$ , two-tailed; Fig. S3). The positive relationship seen between the two sensory modalities in the CI group contradicts the popular, yet simplistic and unsubstantiated, theory of a visual-to-auditory sensory shift within auditory brain regions from pre- to post-implantation. Rather, they provide evidence of an audio-visual coupling, whereby the responsiveness of auditory brain regions to auditory speech increases in synchrony with their responsiveness to visual speech from pre- to post-implantation.

## Discussion

Current CI rehabilitation strategies focus on hearing alone and often discourage the use of vision in the form of lip-reading (17) due to fear of an assumed adverse effect on hearing (18). Here we hypothesised that a decrease in cortical activation to visual speech after implantation would be linked to an increase in activation to auditory speech. However, the findings of this study do not support this hypothesis: longitudinal optical imaging of the human brain presented here reveals that increased cross-modal activation of auditory brain regions by lip-reading neither precludes an increase in cortical responsiveness to auditory speech, nor limits the recovery of speech understanding after implantation. Our findings in cochlear implanted adults parallel recent findings in an animal model showing that cross-modal plasticity within auditory brain regions does not preclude responsiveness to auditory stimulation with a CI, and therefore should not be considered strictly maladaptive as traditionally thought (19). On the contrary, here we show that increased cross-modal activation after adult cochlear implantation is associated with increased auditory responsiveness and better speech understanding with a CI, indicating an adaptive benefit of cross-modal plasticity following implantation.

235 Previous post-implant imaging studies have identified sub-regions which differ in the direction  
236 and extent to which cross-modal STC activation to visual speech correlates with CI outcomes  
237 (8). Given the limited spatial resolution of fNIRS, it is not possible here to interrogate cortical  
238 activation in these individual sub-regions. Furthermore, given the large-scale averaging across  
239 millions of neurons that is inherent to all non-invasive neuroimaging techniques (and to fNIRS  
240 especially), it is not possible to classify whether it is the same population of neurons in the STC  
241 that is responding to the visual stimulus in the CI and NH groups, nor to characterise their  
242 precise nature. Therefore, while we use the term ‘cross-modal’ to refer to putatively auditory  
243 brain regions being cross-activated by a different modality (vision), it is possible that this  
244 activation may be multimodal in its nature (i.e. reflects the activity of multi-sensory neurons  
245 that respond to both auditory and visual inputs). Nonetheless, despite greater spatial averaging,  
246 our findings show that changes from pre- to post-implantation in temporal-lobe activation by  
247 visual speech are functionally relevant to CI outcome.

248

249 Our findings argue against the common view that visual language has a maladaptive effect on  
250 CI success due to cross-modal plasticity within auditory brain regions, indicating that the  
251 effects of cross-modal plasticity on sensory restoration are more complex than previously  
252 thought (5). Rather, our results provide novel evidence that increased cross-modal activation  
253 of auditory brain regions by visual speech may offer a facilitative link between the two  
254 modalities that promotes auditory recovery after cochlear implantation. Cross-modal activation  
255 of superior temporal cortex by visual speech may reflect processes such as inner speech and  
256 auditory imagery due to the inherent correspondence that exists between auditory and visual  
257 speech representations (20). In this way, an increase in STC activation to visual speech may  
258 reflect a stronger correspondence or synergy between the modalities that may facilitate auditory  
259 recovery. Indeed, multisensory integration of auditory and visual speech cues can enhance  
260 speech perception, and is a skill shown to be enhanced in cochlear implant users compared to  
261 normal hearing individuals (21). Our finding of a synergistic link between the auditory and  
262 visual modality following cochlear implantation appears compatible with this suggestion that  
263 CI users are better multisensory integrators of auditory and visual speech cues (21).  
264 Furthermore, the regions of interest interrogated here include posterior regions of the STC,  
265 which are heavily implicated in audio-visual speech integration (22, 23). Therefore, the positive  
266 relationship observed between the two modalities here may reflect CI users’ continued reliance  
267 on visual speech cues and their integration with auditory information to decipher the degraded  
268 auditory signal provided by the implant (21, 24).

269

270 The underlying mechanisms responsible for yoking together the observed changes in  
271 responsiveness to auditory and visual stimulation within the CI group remain unclear. It has  
272 been proposed that vision may facilitate auditory perceptual learning by guiding top-down  
273 attention to auditory representations (25). As such, it is possible that changes in visual and  
274 auditory responsiveness of the STC over time may be linked through a mediating effect of top-  
275 down attention. It is also possible that the responses we measured from the STC may partly  
276 reflect generalized supramodal linguistic processing, for example of phonological (26) or  
277 semantic information (27). Such supramodal linguistic networks may be increasingly activated  
278 by both audition and vision, as an individual CI patient learns to optimally integrate auditory  
279 and visual information to maximize language understanding. In an animal model, vision has  
280 been shown to play a facilitative role in restoring sound localisation abilities after cochlear  
281 implantation (28). In parallel, our findings provide unique evidence in humans for a synergistic  
282 relationship between audition and vision within auditory brain regions, indicating a facilitative  
283 mechanism between the modalities that underlies the restoration of speech understanding  
284 following cochlear implantation.

285

## 286 **Materials and methods**

### 287 **Participants**

288 The study was approved by the Nottingham 1 Research Ethics Committee (REC reference:  
289 12/EM/0016) and was sponsored by Nottingham University Hospitals NHS Trust (Research &  
290 Innovation reference: 11IH007). All participants gave written informed consent before taking  
291 part. Common inclusion criteria across both groups were: native English speakers, self-reported  
292 normal or corrected-to-normal vision, at least 18 years of age, and able to travel to and take  
293 part in all study assessments. Exclusion criteria were any known language, cognitive, or motor  
294 disorder or previous brain injury.

295

### 296 **CI users**

297 We recruited 17 adults with bilateral profound deafness who had consented to, but had not yet  
298 received, their CI device. The group included two pre-lingually, three peri-lingually, and 12  
299 post-lingually deaf individuals who were heterogeneous in their clinical characteristics (Table  
300 1), as is typical of individuals presenting across CI clinics. All participants met UK national  
301 guidelines for cochlear implantation and had been deemed suitable CI candidates by the

302 Nottingham Auditory Implant Programme. All participants were implanted unilaterally with a  
303 Cochlear™ Nucleus® 6 device with CP910 sound processor that employed the advanced  
304 combination encoder (ACE™) stimulation strategy (see SI Text for further clinical  
305 information). One CI user was excluded from all analyses due to excessive motion and poor  
306 contact between fNIRS optodes and the scalp, resulting in poor data quality. Another CI user  
307 was withdrawn from the study at T1 for unrelated medical reasons.

308

### 309 **Control subjects**

310 Seventeen NH adults were recruited to serve as a control group. All participants had normal  
311 hearing thresholds, defined here as average pure-tone air-conduction hearing thresholds of  $\leq 20$   
312 decibels (dB) across frequencies 0.5, 1, 2 and 4 kHz in both ears. Audiometric testing was  
313 conducted at the beginning of each participant's first study visit. The recruitment of control  
314 subjects was staggered in an attempt to approximately match the group's mean age (57 years  
315  $\pm 16.8$ ) to that of the CI users (58.2 years  $\pm 13.9$ ). Due to attrition, one NH control subject did  
316 not complete testing at T1.

317

### 318 **Experimental design**

319 A longitudinal repeated-measures design was employed. The same neuroimaging and  
320 behavioural tests were administered to all participants at two time points. For CI users, the first  
321 testing session (T0) took place at their earliest convenience after having consented to receive a  
322 CI, but before undergoing surgery ('pre-implantation'). At T0, CI users were tested in their  
323 best-aided condition, i.e. wearing their hearing aids if they used them in everyday conditions.  
324 The second testing session (T1) was conducted approximately six months after activation of  
325 the CI ('post-implantation', average duration of CI use = 6.13 months,  $SD=0.4$ ). At T1, CI  
326 users were tested in their best aided condition wearing their preferred listening devices (i.e. CI  
327 and optional contralateral hearing aid). The mean retest interval between T0 and T1 was 8.2  
328 months ( $SD=1.2$ ).

329

330 NH control subjects similarly underwent testing in two sessions. The T0 – T1 retest interval  
331 was set to mirror that of the CI group as closely as was pragmatically possible, given the  
332 variation in clinical waiting times for the CI operation and device activation. The mean retest  
333 interval between T0 and T1 was 8.1 months ( $SD=0.3$ ).

334

### 335 **Testing conditions**

336 Testing was carried out in a double-walled sound-attenuated booth. Participants were seated in  
337 front of a visual display unit (VDU) at a viewing distance of one metre. Visual components of  
338 the stimuli were presented on the VDU. To reflect the typical level of conversational speech,  
339 auditory components were presented through a centrally located loudspeaker at 65 dB sound  
340 pressure level (SPL; A-weighted root-mean-square level averaged over the duration of each  
341 sentence). See SI Text for further information.

342

### 343 **fNIRS scanning**

344 In each testing session, cortical activation was measured using a continuous-wave fNIRS  
345 system (ETG-4000, Hitachi Medical Co., Japan). The ETG-4000 is a commercial system that  
346 emits a continuous beam of light into the cortex and samples at a rate of 10Hz. The system  
347 measures simultaneously at two wavelengths, 695 nm and 830 nm, to allow for the separate  
348 measurement of changes in oxygenated haemoglobin (HbO) and deoxygenated haemoglobin  
349 (HbR) concentrations. This specific choice of wavelengths has been shown to minimise cross-  
350 talk error between the two chromophores (29).

351

### 352 **fNIRS stimuli**

353 The Institute of Hearing Research (IHR) Number Sentences (20) were presented as speech  
354 stimuli during the acquisition of fNIRS measurements. The corpus comprised digital audio-  
355 visual recordings of 90 sentences, each spoken by both a male and female talker. Each of the  
356 sentences contained between four and seven words, three of which were designated keywords.  
357 For the purpose of this experiment, the speech material was presented in two stimulation  
358 conditions: 1) auditory-only (A-ONLY) where the auditory component was presented but the  
359 visual component was not shown; 2) visual-only (i.e. lip-reading, V-ONLY) where the visual  
360 component of the recording was shown but the auditory component was muted. The speech  
361 material was also presented in an audio-visual condition (auditory and visual components  
362 presented congruently) for the purpose of a separate experiment to be reported elsewhere. In  
363 the A-ONLY condition the background remained uniform and a fixation cross was presented  
364 in place of the talker's mouth. Rest periods consisted of this uniform background and fixation  
365 cross only.

366

### 367 **fNIRS paradigm**

368 Thirty IHR number sentences were randomly selected without replacement for presentation in  
369 each of the conditions, with the restriction that an equal number were spoken by the male and  
370 female talker in each condition. The speech stimuli were presented in a block-design paradigm  
371 interleaved with rest periods. Each block comprised six concatenated sentences, evenly spaced  
372 to fill a 24 s block duration. Five blocks were presented for each stimulation condition. During  
373 these blocks, the participants were instructed to attend to the talker and to always try to  
374 understand what the talker was saying. To encourage sustained attention to the experimental  
375 stimuli, an attentional trial was presented after two of the 15 stimulation blocks. These blocks  
376 were chosen at random, and therefore the attentional trials occurred at unpredictable positions  
377 within the experimental run. Two seconds after the cessation of a chosen block, two alternative  
378 words were presented on either side of the fixation cross; in a two-alternative forced-choice  
379 task, participants were asked to press one of two buttons to indicate which word had been  
380 spoken in the immediately preceding sentence. Following the participant's response, an  
381 additional 5 s rest was added to the start of the ensuing rest period. Rest periods were included  
382 to allow the haemodynamic response elicited by the stimulation block to return to a baseline  
383 level. The durations of the rest periods were randomly varied between 20 and 40 s in 5 s  
384 increments. Prior to fNIRS scanning, participants first completed a short familiarisation run to  
385 ensure that they understood the experimental procedure (see SI Text for further details).

386

### 387 **Optode placement**

388 Two 3×3 optode arrays were placed bilaterally over the subject's temporal lobes. The optode  
389 arrays were positioned on the participant's head so as to ensure good coverage of the superior  
390 temporal cortex (STC, see Fig. 1 and Fig. S4). Optode positioning was guided by the  
391 International 10-20 System (30) to promote consistency across participants and test sessions  
392 (see SI Text for further details).

393

### 394 **Definition of ROI**

395 In order to assess the sensitivity of our fNIRS measurements to the underlying cortical regions,  
396 using the AtlasViewer tool (31) a Monte-Carlo code for simulating the probabilistic path of  
397 photon migration through the head (32) ('tMCimg') was run with  $1 \times 10^7$  simulated photons  
398 launched from each optode position. The resultant sensitivity profiles (Fig. 1) suggested that  
399 channels #9, 10 and 12 (left hemisphere) and channels #20, 21 and 23 (right hemisphere)  
400 provided appropriate sensitivity to the posterior portion of STC. Therefore, these measurement

401 channels were pre-defined as the left and right superior temporal regions of interest (ROIs)  
402 respectively. The left and right ROIs together formed the bilateral STC ROI.

403

#### 404 **Behavioural test of speech understanding**

405 The CUNY Sentence Lists (33) were employed to obtain a measure of speech understanding  
406 (see SI Text for further details). The CUNY Sentence Lists include 25 standardised lists each  
407 comprising 12 sentences that vary in length and topic. Each list contains between 101 and 103  
408 words spoken by a male talker.

409

410 For the purpose of this experiment, two CUNY lists (i.e. 24 sentences) were randomly selected  
411 without replacement for presentation in the A-ONLY stimulation condition. Speech  
412 understanding in V-ONLY and AV modalities was also tested for the purpose of a separate  
413 experiment to be reported elsewhere. The 24 sentences were presented in random order. After  
414 each sentence presentation, the participant was instructed to repeat back all words that they  
415 were able to identify. All words correctly reported by the participant were recorded by the  
416 researcher on a scoring laptop before initiation of the next trial. The scoring method ignored  
417 errors of case or declensions. Prior to commencement of speech understanding testing, all  
418 participants completed a short familiarisation run (see SI Text).

419

#### 420 **Processing of fNIRS data**

421 Raw fNIRS recordings were exported from the Hitachi ETG-4000 into MATLAB for use with  
422 routines provided in the HOMER2 package (34) and custom scripts. To prepare the recordings  
423 for subsequent analyses they were subjected to a set of pre-processing steps, including motion-  
424 artefact correction, bandpass filtering, and haemodynamic signal separation. Full details of all  
425 pre-processing steps are provided in SI Text. In order to quantify the level of cortical activation,  
426 the pre-processed fNIRS signal was subjected to an ordinary least squares general linear model  
427 (GLM). The GLM design matrix included three boxcar regressors, one for each of the  
428 stimulation conditions. The two response periods following the two attentional trials were also  
429 modelled in the design matrix as isolated events occurring at the time the two words were  
430 presented on screen. These were convolved with the canonical haemodynamic response  
431 function provided in SPM8 [<http://www.fil.ion.ucl.ac.uk/spm>]. After completing the first-stage  
432 OLS estimation at the single-subject level, we used the Cochrane-Orcutt procedure (35) to  
433 correct for serial correlation. Briefly, this involved fitting a first-order autoregressive process

434 to the model residuals and transforming the original model according to the estimated  
435 autoregressive parameter (see (36)). We then re-estimated the beta weights based on the  
436 transformed model (second stage).

437

438 The beta weights of the canonical haemodynamic response function term were extracted at  
439 each measurement channel, for each stimulation condition, and for all participants. The  
440 haemodynamic signal separation method employed here (37) (SI Text) assumes a fixed linear  
441 relationship between HbO and HbR in the functional response. Therefore, the results of all  
442 statistical analyses are identical regardless of whether conducted on the beta weights extracted  
443 for the HbO or HbR parameter. For simplicity, only results pertaining to the beta estimates of  
444 the HbO parameter of the functional component are presented here. These beta weights were  
445 used to quantify the amplitude of cortical activation for each condition compared to rest. The  
446 resultant beta weights were averaged across the ROI measurement channels for each group and  
447 at each time point and were subjected to further statistical analysis as outlined below.

448

#### 449 **Processing of behavioural data**

450 Speech understanding, measured using the CUNY Sentence Lists, was quantified as the  
451 percentage of words reported correctly (% correct). In order to make the data more suitable for  
452 statistical analysis, the rationalised arcsine transform (38) was applied using Matlab (see SI  
453 Text for details). Subsequently, the transformed scores (rationalised arcsine units, RAUs) were  
454 subjected to statistical analysis.

455

#### 456 **Statistical analysis**

457 Following the pre-processing of neuroimaging and behavioural data, resultant data were  
458 analysed and figures produced using IBM® SPSS® Statistics software (Release 22.0, Armonk,  
459 NY: IBM Corp.). Data and analysis scripts are publically available through the University of  
460 Nottingham's Research Data Management Repository.

461

#### 462 **Linear mixed model analysis**

463 The ROI beta weights were analysed separately for the bilateral, left and right ROI using a  
464 linear mixed model (LMM, see SI Text for further information). Each model included two  
465 fixed factors of 'group' and 'time' in order to estimate the fixed effect of experimental group  
466 (CI users versus NH controls) and time relative to implantation (T0, before implantation; T1,

467 six months after CI activation) on cross-modal activation. In addition, a ‘group – time’  
468 interaction term was specified in order to understand whether an effect of time on cortical  
469 activation differed between the two groups. Specifically, if a group – time interaction indicated  
470 that cross-modal activation changed over time in the CI group but remained comparatively  
471 stable in the NH group, this would suggest an effect specific to the CI process.

472

### 473 **Correlational analysis**

474 Change in amplitude of cross-modal activation from pre- to post-implantation was calculated  
475 as the difference between the amplitude (beta weight) of STC activation to visual speech  
476 measured at T0 and T1. Bivariate correlation analysis was conducted to examine the nature of  
477 the relationship between change in cross-modal activation ( $\Delta$  beta weight) and speech  
478 understanding (RAU). Specifically, the parametric statistic Pearson’s correlation coefficient ( $r$ )  
479 was used to estimate the direction and strength of the linear relationship. Similarly, Pearson’s  
480 correlation was conducted to examine the direction and strength of the relationship between  
481 change in cross-modal activation and change in amplitude of STC activation to auditory speech  
482 (‘auditory responsiveness’).

483

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492

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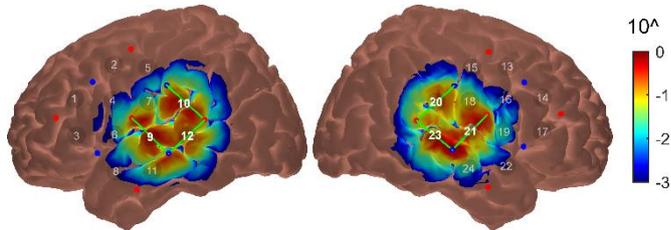
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 598

599 **Figure legends**

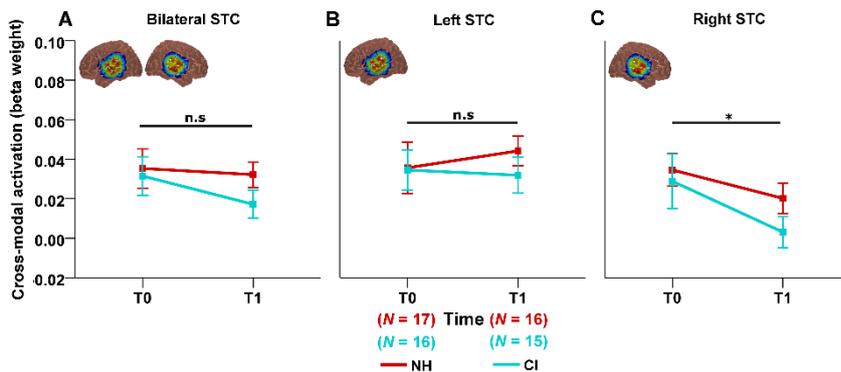
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602 **Figure 1: Sensitivity profiles for cortical regions of interest.** Left hemisphere measurement  
 603 channels (#9, 10 and 12) and right hemisphere measurement channels (#20, 21, and 23) are  
 604 highlighted. Colour scale depicts relative sensitivity to hypothetical cortical activation  
 605 logarithmically from 0.001 to 1.

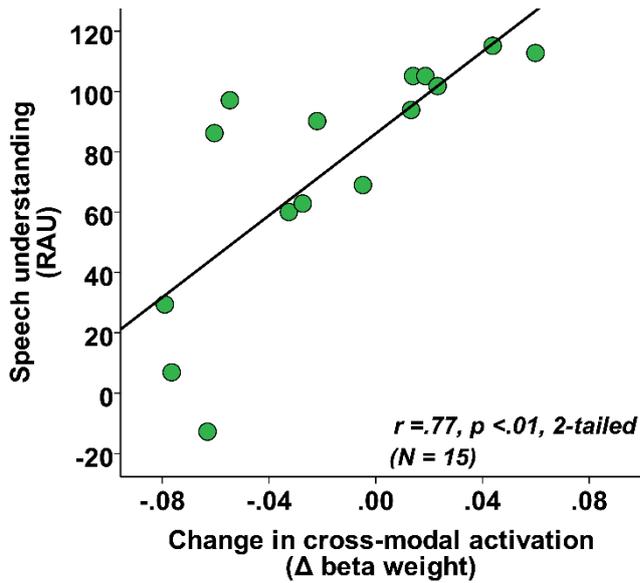
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607

608 **Figure 2: Group-averaged amplitude of cross-modal activation before and after**  
 609 **implantation.** Group-averaged amplitude of cross-modal activation of STC by visual speech  
 610 (in beta weight) of (A) bilateral STC, (B) left STC, and (C) right STC. Inset cortical images  
 611 illustrate the sensitivity profile for the cortical regions of interest. \* $P < .05$  main effect of time  
 612 when assessed across both groups combined, based on the estimated marginal means from the  
 613 linear mixed model analysis. n.s., non-significant. Error bars represent  $\pm 1$  standard error. CI,  
 614 cochlear implant users; NH, normal-hearing controls; T0, pre-implantation; T1, post-  
 615 implantation.

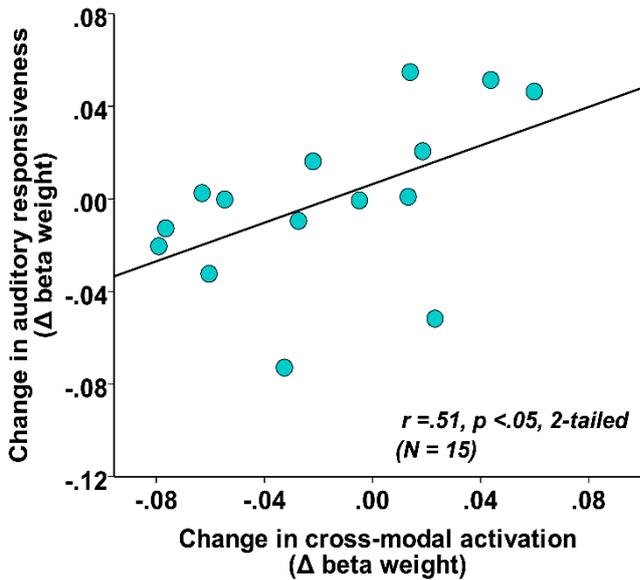
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617

618 **Figure 3: Relationship between change in cross-modal STC activation and speech**  
 619 **understanding.** Change in cross-modal activation of bilateral STC by visual speech ( $\Delta$  beta  
 620 weight; arbitrary units) from T0 to T1 is plotted against speech understanding at T1 (RAU),  
 621 with the regression line shown.

622



623

624 **Figure 4: Change in cross-modal STC activation and auditory responsiveness.** Change in  
 625 cross-modal activation of bilateral STC by visual speech from T0 to T1 ( $\Delta$  beta weight;  
 626 arbitrary units) is plotted against change in bilateral auditory responsiveness from T0 to T1  
 627 with the regression line shown.

628