Visual stimuli modulate local field potentials but drive no high-frequency activity in human auditory cortex

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Abstract

Neuroimaging studies suggest cross-sensory visual influences in human auditory cortices (AC). Whether these influences reflect active visual processing in human ACs, which drives neuronal firing and concurrent broadband high-frequency activity (BHFA; >70 Hz), or whether they merely modulate sound processing is still debatable. Here, we presented auditory, visual, and audiovisual stimuli to 16 participants with stereo-EEG depth electrodes implanted near ACs for presurgical monitoring. Anatomically normalized group analyses were facilitated by inverse modeling of intracranial source currents. Cross-correlation and spatiotemporal pattern similarity analyses suggested cross-sensory visual influences, which lagged auditory responses by several tens of milliseconds in ACs. Visual stimuli also modulated the phase of intrinsic low-frequency oscillations and triggered 15–30-Hz event-related desynchronization in ACs. However, BHFA, a putative correlate of neuronal firing, was not significantly increased in ACs after visual stimuli, not even when they coincided with auditory stimuli. Intracranial recordings demonstrate cross-sensory modulations, but no indication of active visual processing in human ACs.

Introduction

Many previous studies support the view that cross-sensory visual information influences the function of human AC, possibly involving even primary areas [1-4]. The exact functional significance of these early cross-sensory influences, however, remains still unclear. A more conservative theory suggests that cross-sensory influences play a modulatory role in early sensory areas including ACs, to enhance relevant and suppress irrelevant ascending inputs, akin to the effects of selective attention. This hypothesis is supported by neurophysiological evidence that the effects of unimodal visual stimuli on ACs are limited to subthreshold synaptic influences [5-7]. For example, laminar extra-cellular recordings in the non-human primate (NHP) AC suggest that when presented alone, cross-sensory visual stimuli modulate the phase of neuronal oscillations but do not evoke increased neuronal firing detectable in the analysis of multiunit activity [8]. Similarly, systematic neurophysiological recordings in rodents suggest that the prevalence of individual neurons activated to other than sensory-specific inputs is very low in sensory areas including AC [9].

Classically, integration across senses has been thought to be mediated by neurons that show increased firing activity to concurrent multisensory inputs. These effects were originally quantified as *multisensory interactions* (MSI), changes in firing rates of individual neurons, which are non-additive and which are strongest for faint or noisy stimuli [10]. For example, MSIs between a faint sound and spatially and temporally coinciding visual [10] or tactile [11] stimulus result in activations stronger than the sum of the respective unimodal activations. Neurophysiological evidence for such MSI effects has been obtained from higher areas [12, 13], but whether the human ACs contains populations of neurons that increase their firing rate and synchrony when sounds are coupled with visual stimuli is still uncertain. One previous NHP model suggested that despite the significant effects observable in local field potential (LFP) responses, measures of firing activity were concurrently suppressed rather than increased [6]. Effects such as these would support the more conservative hypothesis that cross-sensory influences modulate but do not activate neurons in ACs.

However, many previous findings have been interpreted to provide support for a more provocative hypothesis that multisensory processing occurs even in early human AC [14-16]. This hypothesis has gained most direct support from neurophysiological studies in animal models, including single-unit recordings in non-human

primates [17] and other mammals [9, 18, 19], which provide evidence for cross-sensory firing activity in ACs. According to one of these studies, which was conducted in the ferret model, cross-sensory stimuli drive single-unit firing patterns that convey information of the properties of visual stimuli in ACs [18]. Similar findings emerged in a recent study that suggested firing activity to visual stimuli in the deep infragranular layers of mouse AC [20]. These findings would suggest that instead of being only modulated by cross-sensory influences, AC neurons may actively process visual information.

Whether influences such as those seen in animal models occur also in the human AC is difficult to examine using conventional non-invasive neuroimaging paradigms. The bulk of human neuroimaging evidence of AC responses triggered by unimodal cross-sensory stimuli consists of studies using MEG/EEG [3, 21] and fMRI [4, 14], which offer limited means for making inferences of neuronal mechanisms. At the same time, the few previous studies using intracranial recordings to investigate cross-sensory influences of simple non-verbal stimuli in ACs have typically been limited to relatively small samples of participants (N=3-8) and focused on individual-level statistical approaches [16, 22], which may limit the generalizability of results.

Here, we tested the hypothesis that human ACs are not only modulated, but also activated by cross-sensory visual stimuli. To this end, we employed intracranial stereo-EEG (SEEG) recordings in a relatively large sample of patients (N=16) who had depth electrodes implanted in or near auditory cortical areas for preoperative monitoring. This methodology provides direct measurements of LFPs from the neuronal tissue, to quantify broadband high-frequency activity (BHFA, above 70 Hz) activity. In contrast to gamma band oscillations that are also visible to MEG and EEG, BHFA signals are believed to be a reliable correlates of local spiking activity [23-26]. Another benefit of using SEEG data is that the recording contacts of depth electrodes extend across the depth of the superior temporal plane help reveal the patterns of auditory vs. cross-sensory responses at a much greater detail than what is possible with non-invasive recordings, or even with subdural electrocorticography (ECoG). A challenge in previous human SEEG studies of cross-sensory modulation of human ACs has been that the clinically determined anatomical implantation plans vary between participants, thereby complicating robust hypothesis-testing at the group level [16, 27]. Here, to facilitate group analyses, we complemented

traditional "electrode-space" analyses with our recently introduced surface-based source modeling technique that estimates the neuronal activity in the anatomically normalized cortical "source space" [28].

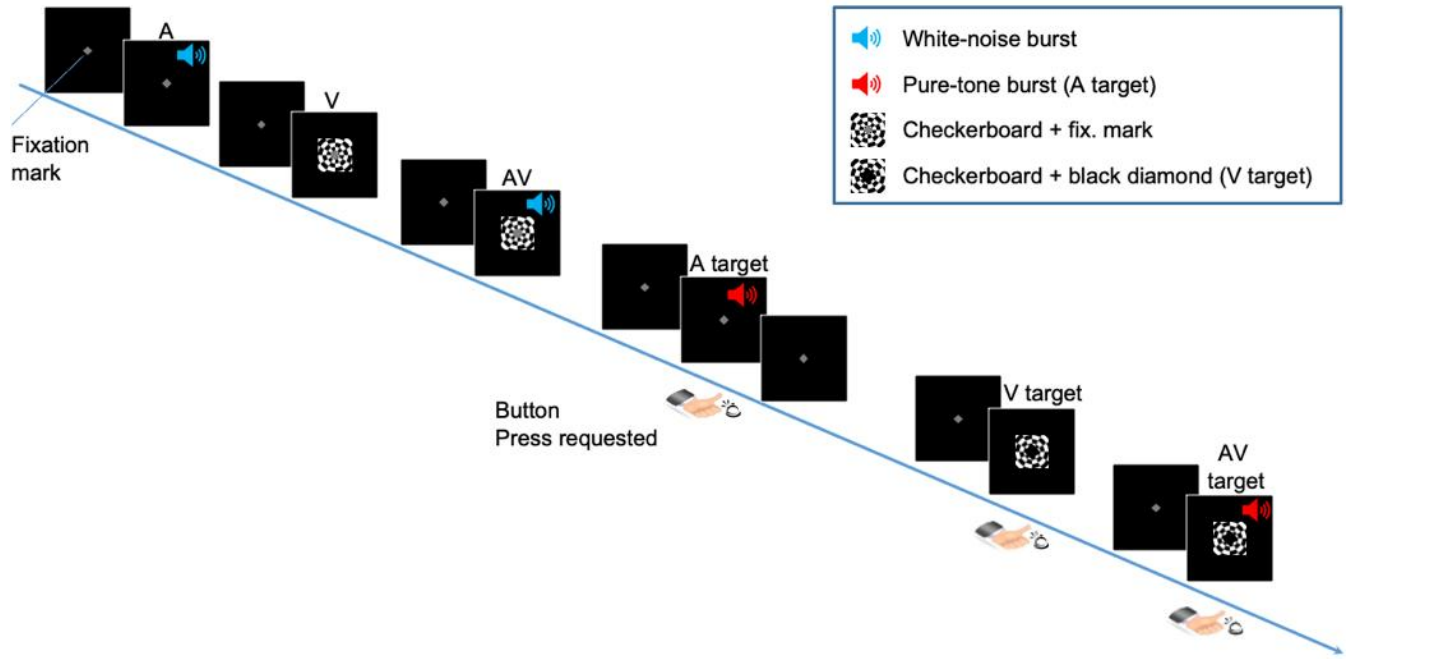

Figure 1. Stimuli and task. Participants were presented with simple A, V, and AV stimuli. In an oddball design, they were asked to press a button upon hearing a rare A, V, or AV target stimulus among frequent non-targets. The non-targets were A noise bursts, V checkerboard patterns, or their AV combinations. The A targets were A pure tones, V targets diamond shapes embedded within a checkerboard, or their AV combinations.

Results

To investigate cross-sensory influences in AC, we presented auditory (A), visual (V), and audiovisual (AV) stimuli to 16 participants with stereo-EEG (SEEG) depth electrodes implanted near ACs for presurgical monitoring. The stimuli were presented in a randomized order, at a 1.2–2.8 s jittered inter-stimulus interval (ISI; mean 2 s) during SEEG recordings (**Fig. 1**). Using this design, we found strong evidence of subthreshold modulatory effects, reflected as "phase resetting" of ongoing intrinsic low-frequency oscillations and enhanced event-related desynchronizations (ERDS) of 15-30 Hz beta oscillations in ACs. Furthermore, our analyses suggested significant pattern similarity to Laplacian referenced [29] trial-averaged responses to A and V stimuli across the contacts of SEEG depth electrodes passing through superior temporal areas (i.e., "sT" electrodes). According to our cross-correlation analyses, these visual LFP influences lagged intra-modal auditory LFPs by about 50 ms.

However, although the participants significantly benefited from combining information from the two modalities in terms of the behavioral reaction times (RT), there was little evidence of enhanced BHFA to V stimuli, whether presented alone or in combination with A stimuli in our group analyses.

Behavioral results

All 16 participants were able to perform the task according to the instruction: On average, they were able to detect almost all targets in auditory (A), visual (V), and audiovisual (AV) conditions, with no statistically significant differences in proportions of correct responses (PCR) between the conditions. The mean ± standard error (SEM) values of PCR for A, V, and AV target stimuli were PCR_A = 0.92 ± 0.04; PCR_V = 0.93 ± 0.04 and PCR_{AV} = 0.94 ± 0.03, respectively. The high PCR value for the unimodal V targets provides evidence that the participants were able to focus their gaze according to the instruction. Evidence for significant advantages of combining A and V stimuli were found in RTs to correctly detected target stimuli. The mean ± SEM values of RT for A, V, and AV conditions were RT_A = 668 ± 24 ms, RT_V = 575 ± 19 ms, and RT_{AV} = 546 ± 24 ms, respectively. The RTs were significantly faster to AV targets than to A targets (t_{15} = -5.6, $p_{Corrected}$ < 0.001; Cohen's d= -1.5), as well as to AV targets than to V targets (t_{15} = -3.0, $p_{Corrected}$ < 0.05; d=-0.8).

Event-related responses in superior temporal electrode contacts

Previous non-invasive studies in humans warrant a hypothesis that cross-sensory responses to simple V stimuli are elicited in auditory cortices, lagging the first A responses by several tens of milliseconds [3]. To evaluate this hypothesis, we analyzed trial-averaged SEEG responses in the superior temporal sT electrode using bipolar referencing strategy, where each contact is referred to its medial neighbor by subtraction. This helps control the contribution of volume-conducted signals from further away of the contacts of interest, recently suggested to pose a significant bias for the interpretation of local-field potential (LFP) findings in ACs [30]. As demonstrated by the trial averaged SEEG data shown in **Fig. 2a** (Subject 4) and in **Suppl. Figs. S1** and **S2**, responses to V stimuli were considerably weaker and had a smaller SNR in comparison intramodal A inputs. Therefore, we tested our hypothesis based on a data-based strategy. In each participant, we computed cross-correlations between the absolute values of A and V responses during 0-300 ms after the stimulus onset (xcorr.m, Matlab; sT contact showing evidence of early V activity exceeding baseline variability). According to this analysis, the

median lag between the V response and A response was 72 ms (median absolute deviation 31 ms) (**Fig. 2c-e**). At the group level, the lag was significantly larger than zero (Wilcoxon signed rank test, $p<0.001$, Signed Rank = 91). Only subjects with more than four adjacent contacts with acceptable signal quality in the sT electrode were included in this analysis (N=13 subjects). The A and V responses in each participant's sT contact that was used for this analysis are shown in the y-y-plot (which normalizes the amplitude scales of each class for visualization) in **Suppl. Fig. S3**.

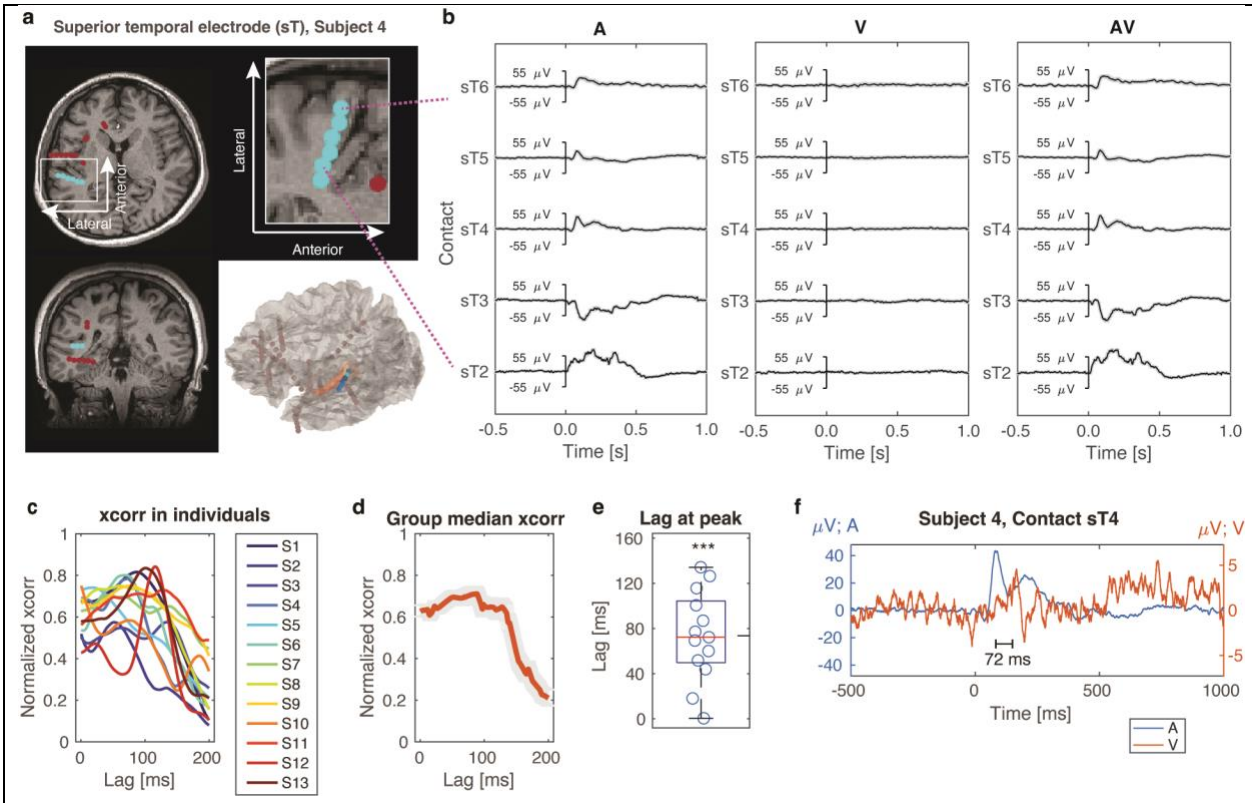

Figure 2. Analysis of trial-averaged even-related responses. (**a**) The locations of the superior temporal (sT) electrode contacts (cyan dots) and (**b**) respective responses with bipolar referencing to A, V, and AV stimuli in a single participant (red dots refer to other than sT contacts). The contacts numbering ascends from medial to lateral. Each contact has been referred to its more medial neighbor (*e.g.*, sT2 refers to sT2-sT1). The thin gray shading depicts standard error of mean, SEM, across the trials (**Suppl. Figs. S1** and **S2** show data from other participants**)**. (**c**) Normalized cross-correlation values of individuals, focused *a priori* in the range where positive peak values of xcorr(abs(A),abs(V)) suggest that V lags A. (**e**) Group median of the normalized cross-correlation values. (**e**) Box plot of the V-to-A lag values determined from the peaks of cross-correlogram. The circles refer to individual participant values. At the group level, the lag was significantly larger than zero (***$p<0.001$, Wilcoxon test). (**f**) A and V responses in the contact sT4 used for calculating the cross-sensory

lags in a single participant (Subject 4). The left side of the y-y plot reflect the auditory response, and the right side reflects the scale of the visual response. The 72-ms scale bar refers to this participant's lag suggested by the cross-correlation analysis, which also equals to the group median of the lags.

Spatiotemporal similarity of sT responses to auditory vs. visual stimuli

Our second hypothesis was that cross-sensory V modulate the same supratemporal source population as that also responding to A stimuli. To test this hypothesis, we compared responses to A and V stimuli using a spatiotemporal similarity analysis, which based on the correlation between two signals across contacts and time (**Fig. 3**). This analysis was conducted across the contacts in sT depth electrodes, in the subsample of 13 participants with a sufficient number of contact data. As shown the data in **Fig 3a** and **Suppl. Fig. S4**, the response pattern to V stimuli were qualitatively very similar to those generated to A stimuli, despite the differences in the response magnitudes between the two conditions. To quantify the similarity of V vs. A activation patterns at the group level, we compared the respective spatiotemporal patterns in sliding 300-ms windows before and after the stimulus onset (**Fig 3b**)**.** Within each 300-ms window, the matrices of contact-specific Laplacian-referenced traces of A and V responses (*i.e.*, every contact referred to the average of its immediate neighbors) were reshaped to vectors. We then calculated the Kendall tau values for each time-window and participant. The tau values were Fisher-transformed for group statistics, which was calculated using a non-parametric maximum-statistic permutation strategy (for details, see Methods). As shown by the results depicted in **Fig. 3b**, the group averages of similarity values exceeded the critical value (z>0.16, $p_{\text{Corrected}}$<0.05, maximum-statistic permutation test) after the post stimulus period, starting from the sliding window centered at 94.3 ms post stimulus onset. Each individual's data are show in the rightmost panel of **Fig. 3b**.

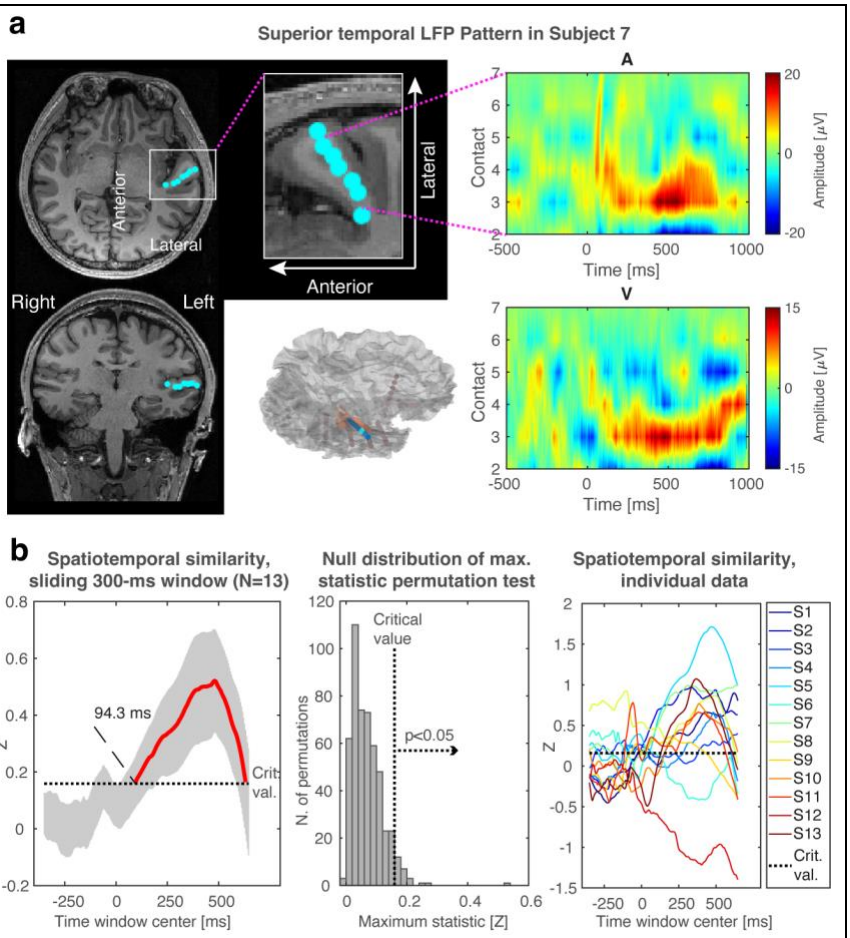

Figure 3. Spatiotemporal pattern similarity analysis in the sT electrode. (**a**) Laplacian-referenced (each contact referred to the average of its immediate neighbors) spatiotemporal patterns to A and V stimuli in Subject 7. The analyzed sT contacts (cyan dots) are projected to one MRI slice. (**b**) Group-level spatiotemporal similarity analysis in a 300-ms sliding time window. At each step, the corresponding A and V signal matrices across *n* time samples within the 300-ms window and *m* contacts were reshaped to vectors with $n \times m$ elements. Kendall correlation coefficients were then computed step-by-step and Fisher-transformed for group analyses. Maximum-statistic permutation test was employed to address multiple-comparison problems. The rightmost panel shows the individual correlations. Error bars refer to the standard error of mean.

Time-frequency representation of SEEG power

Recent single-unit recordings in non-human primates [17] and other mammals [9, 18, 19], including very recent studies in the mouse AC [20], suggest that instead of modulatory influences only (**Figs. 2,3**), cross-sensory V stimuli could trigger supra-threshold activations in AC neurons, reflecting active processing of visual information. Here, we utilized two strategies to analyze BHFA, a putative correlate of multiunit firing activity in the nearby regions [23, 31], to test this hypothesis at the group level:

(**i**) For each subject, we determined the electrode contacts that were closest to the centroids of three cortical Human Connectome Project (HCP) labels across the auditory hierarchy (**Figs. 4a, 5a, and 6a**; **Suppl. Fig. S5**). Our primary focus in the electrode-level analyses was the contact closest to the HCP label "early auditory cortex" (AC) (**Figs. 4b, 5b**). The group analysis results regarding contacts closest to the HCP labels "auditory association

cortex" (AAC) and "temporo-parieto-occipital junction" (TPOJ) are included as Supplementary Material (**Suppl. Fig. S5**).

(**ii**) A limitation of the electrode-contact analysis is that the recording sites, which were determined by clinical reasons only, differ between the participants. Therefore, to allow for anatomically normalized analyses across the auditory processing hierarchy, we used our recently developed SEEG source modeling approach [28]. Hypothesis testing was conducted using LME models analogous to those used for electrode-contact analyses in the cortical ROIs AC, AAC, and TPOJ (**Figs. 4c and 5c)**.

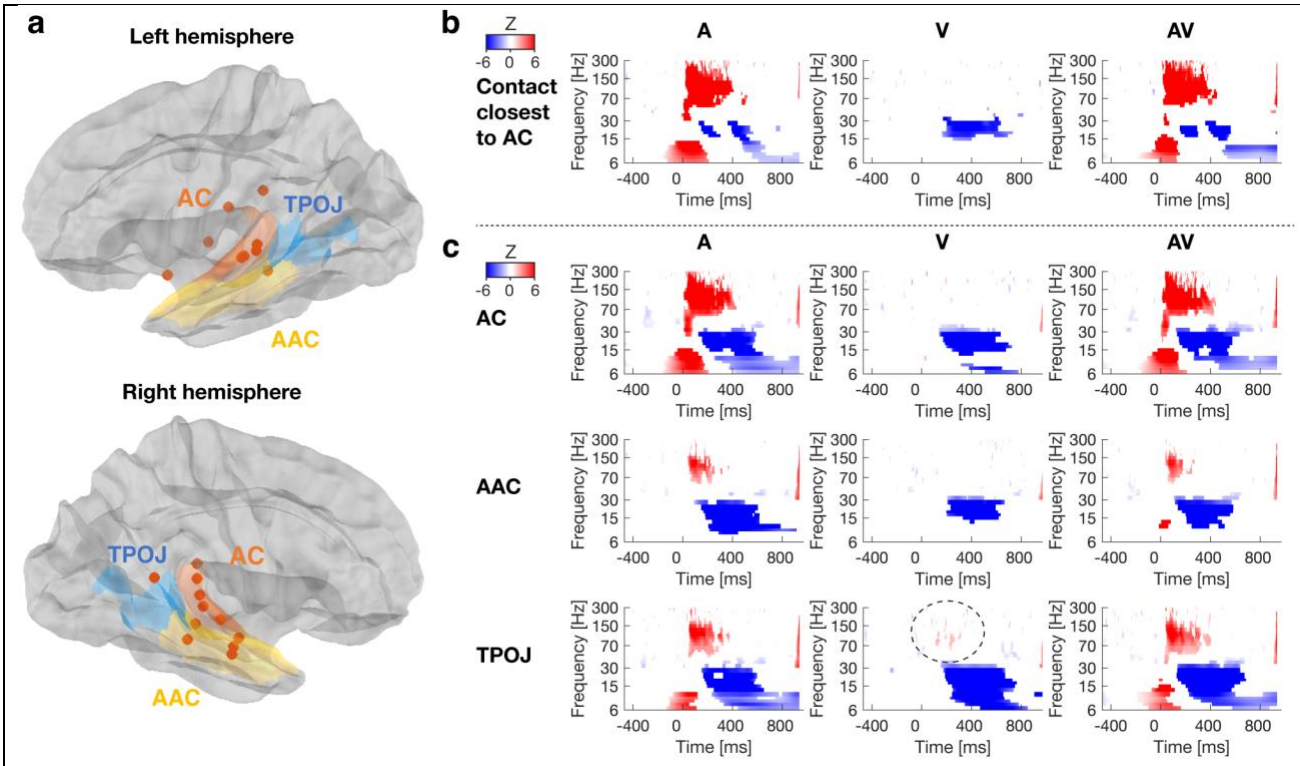

Figure 4. Group analysis of power TFRs. (**a**) Analysis sites in the standard brain representation. Each subject's SEEG contact that was closest to AC is marked with an orange dot. The orange, yellow, and blue labels show the three ROIs used for the source-modeling analysis, determined based on the HCP atlas. (**b**) TFRs to A, V, and AV stimuli in the electrode contact that was in each subject closest to AC. Statistically significant BHFA (>70 Hz, FDR-adjusted p<0.05) emerged to A and AV stimuli only. Cross-sensory V stimuli suppress beta (15-30 Hz) power 200 ms after the stimulus onset. (**c**) ROI analysis of SEEG source estimates. Consistent with the electrode-contact analysis, cross-sensory V triggered suppression of beta and theta/alpha (6-15 Hz) power across the studied ROIs. Traces of weak but significant (FDR-adjusted *p*<0.05) enhancement of BHFA was observed only in TPOJ (encircled). The TFRs depict group averages of the effect size *z* in individual subjects, masked to time/frequency elements with statistically significant effects (FDR-adjusted *p*<0.05) [32]. Individual subjects' frequency-wise *z* values were determined by subtracting the mean baseline power from each TFR element and then dividing them by the baseline SD. Data from both hemispheres were included a single linear mixed effects (LME) model to determine the statistical significance.

TFRs of baseline-normalized signal power values to A, V, and AV stimuli in these contacts of interest and the respective ROIs were then entered to linear mixed effects (LME) models comparing to the pre-stimulus baseline and determining the differences between AV-(A+V), AV-A, and AV-V contrasts (**Figs. 4, 5**). These LME models assessed the statistical significance of the intercept while controlling for the fixed effect of implanted hemisphere and the random effect of subject identity at all time and frequency instances, with the p-values corrected for

multiple comparisons using the false discovery rate (FDR) procedure of [32]. The critical p value was determined jointly across all conditions/contrasts and contacts-of-interest at 0-500 ms and 6-250 Hz.

Stimulus condition effects: In the contact closest to the HCP label AC, TFRs to A and AV stimuli showed a characteristic event-related pattern where statistically significant (FDR-adjusted $p<0.05$) early power increase (or "event-related synchronization", ERS) at the 6-15 Hz theta/alpha range is followed by a beta-range (15-30 Hz) power suppression (or "event-related desynchronization", ERDS; **Fig. 4b**). At the group level, this theta/alpha-beta ERS/ERDS pattern was coupled with a significant (FDR-adjusted $p<0.05$) sustained increase of BHFA. Interestingly, the beta-range ERDS was equally clear to V stimuli alone, suggesting statistically significant (FDR-adjusted $p<0.05$) cross-sensory modulation of beta-range oscillations in or near human ACs, which started around 200 ms after the stimulus onset. However, no evidence of increases of BHFA, a putative marker of underlying firing activity, were found in the contact closest to AC. The results for contacts closest to the HCP labels "auditory association cortex" (ACC) and "temporo-parieto-occipital junction" (TPOJ) are described in the Supplementary Material (**Suppl. Fig. S5**).

The A, V, and AV stimulus-related power TFRs of each individual participant's contact closest to AC are shown in **Supplementary Fig. S6**. In this individual-level analyses, the single-trial TFR power was compared to pre-stimulus baseline using paired *t*-tests across all trials. The purpose of comparisons against the baseline was also to normalize the TFRs across frequencies to mitigate the 1/f trend of signal power. To avoid false negatives in our interpretation of the lack of BHFA to V stimuli in ACs, we used no correction for multiple comparisons in these specific single-participant analyses. Despite the inclusive criterion, in the electrode-contact-space, evidence of more robust increase of visual BHFA, deemed qualitatively different from pre-stimulus noise, was found in only one participant, Subject 8. (**Suppl. Fig. S6**). However, in this participant, the contact that was in the 3D volume closest to early AC appears to be, in fact, located closer to the fundus of STS (a classic multisensory area) than AC, per se (**Suppl. Fig. S7**).

Results of our anatomically normalized group ROI source-modeling analysis agreed with the SEEG contact analysis (**Fig. 4c**). At the lower frequency range, responses to A and AV stimuli were characterized by an early theta/alpha ERS (<200 ms, FDR-adjusted $p<0.05$), followed by a longer-lasting beta ERDS (<30 Hz, FDR-

adjusted $p<0.05$). Consistent with the electrode-contact analysis, this later lower-frequency ERDS effect was also prominently significant to V stimuli alone (FDR-adjusted $p<0.05$), constituting the strongest putatively cross-sensory influence across the auditory hierarchy in the present study. As for the BHFA range, statistically significant (FDR-corrected $p<0.05$) power increases were observed to A and AV stimuli alone in AC, AAC, and TPOJ areas. No significant increases of cross-sensory BHFA were observed to V stimuli in AC or AAC. Traces of significantly increased BHFA to V stimuli were, however, observed in the area TPOJ (FDR-adjusted $p<0.05$). **Supplementary Figure S8** shows the corresponding source modeling results in each individual subject.

Contrast between stimulus conditions: The group analysis of TFRs from the contact closest to AC suggested significant (FDR-adjusted $p<0.05$) superadditive MSI effects, determined from the AV-(A+V) contrast, at the beta range (**Fig. 5b**). Other than the confirmatory contrast between AV and V conditions, where power changes to a stimulus containing auditory information vs. no auditory information are non-surprising, there was no evidence that the simultaneous presentation of A and V stimuli increases BHFA in the contact closest to AC. Similar to the electrode-contact analysis, the results of source modeling ROI analyses suggested significant (FDR-adjusted $p<0.05$) superadditive MSI effects in AC, as well as in AAC and TPOJ, which occurred at the theta and beta ranges. In the AV vs. A contrast, we also observed significant increases of early high alpha activity and subsequent beta ERDS effects. Besides the anticipated BHFA effects in the AV-V contrast, the only evidence of increased BHFA was in the AV-A contrast in TPOJ. In particular, no other BHFA effects were observed to AV-(A+V) or AV-A contrast. Results for the condition contrasts in the electrode contacts closest to AAC and TPOJ are shown in **Supplementary Figure S9**.

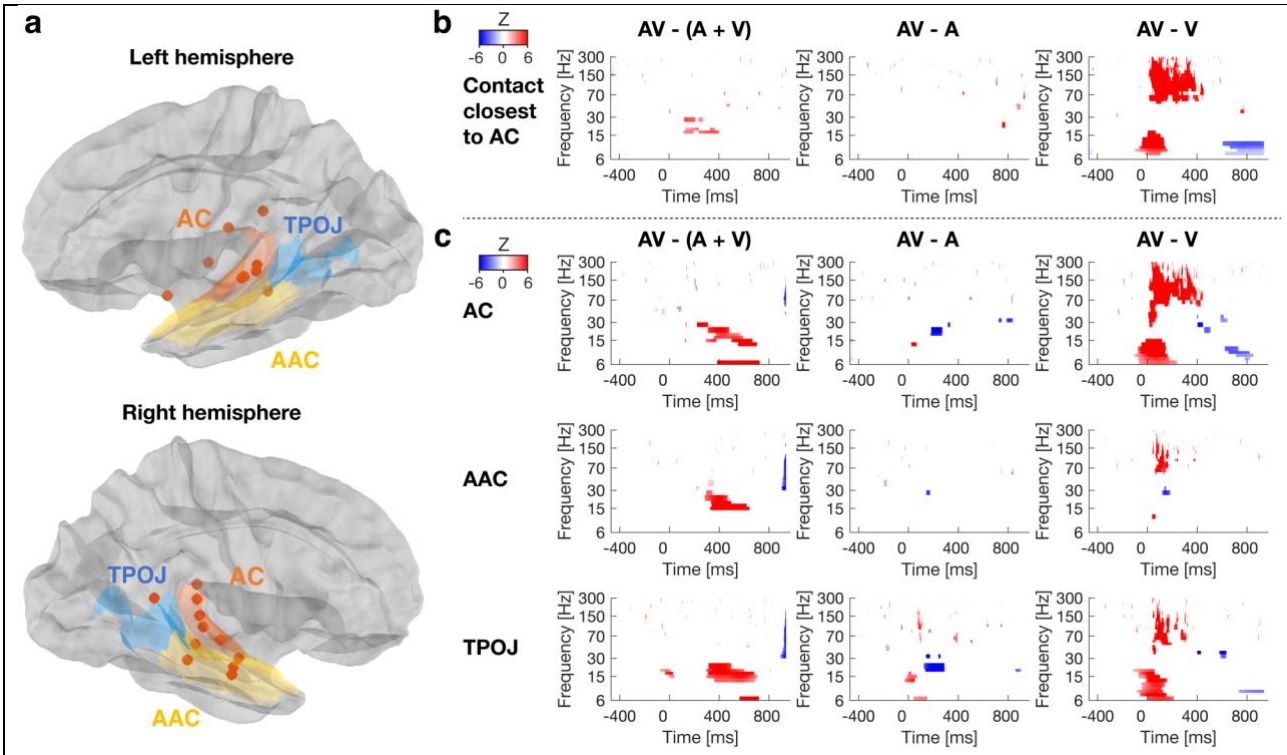

Fig. 5. Group analysis of power TFR contrasts between conditions. (**a**) Analysis sites in the standard brain representation. Each subject's SEEG contact that was closest to AC is marked with an orange dot. The orange, yellow, and blue labels show the three ROIs used for the source-modeling analysis, determined based on the HCP atlas. (**b**) TFR contrasts in the electrode contact closest to AC. Indices of statistically significant (FDR-adjusted p<0.05) multisensory interactions (MSI) occur at the beta range in the AV-(A+V) contrast. The contrast AV-V showed the anticipated enhancement of BHFA and early-latency theta/alpha in AC. (**c**) ROI analysis of source estimates. Indices significant of low-frequency MSIs were observed in all ROIs (FDR-adjusted p<0.05). In addition, beta power was significantly suppressed in AC and TPOJ in the AV-A contrast. Apart from the anticipated effects in the AV-V contrast, there was no evidence of effects at the BHFA range. The TFRs depict group averages of the baseline-normalized power, determined identically to the data in **Fig. 4**, masked to time/frequency elements with statistically significant effects (FDR-adjusted *p*<0.05) [32]. Data from both hemispheres were included a single linear mixed effects (LME) model.

Intracranial inter-trial phase consistency

In the light of previous studies in non-human primates [8], we tested whether cross-sensory stimuli affect the phase of ongoing oscillations in human AC. The results suggest significant increases of low-frequency inter-trial phase consistency (ITPC) after V stimuli, both in the electrode contact closest to AC (**Fig. 6b**) and in all three source-modeling ROIs across the auditory processing hierarchy (FDR-adjusted p<0.05) (**Fig. 6c**). In the contact analysis, this ITPC effect was significant already about 100 ms after the onset of V stimuli. Most interestingly,

the cross-sensory ITPC increases across the auditory processing hierarchy occurred at time/frequency windows where there was no evidence for concurrent increases of TFR power. ITPC values in the electrode contacts closest to AAC and TPOJ are shown in **Suppl. Fig. S10**. The results of ITPC contrasts between conditions are shown in Supplementary Material (**Suppl. Figs. S11, S12**).

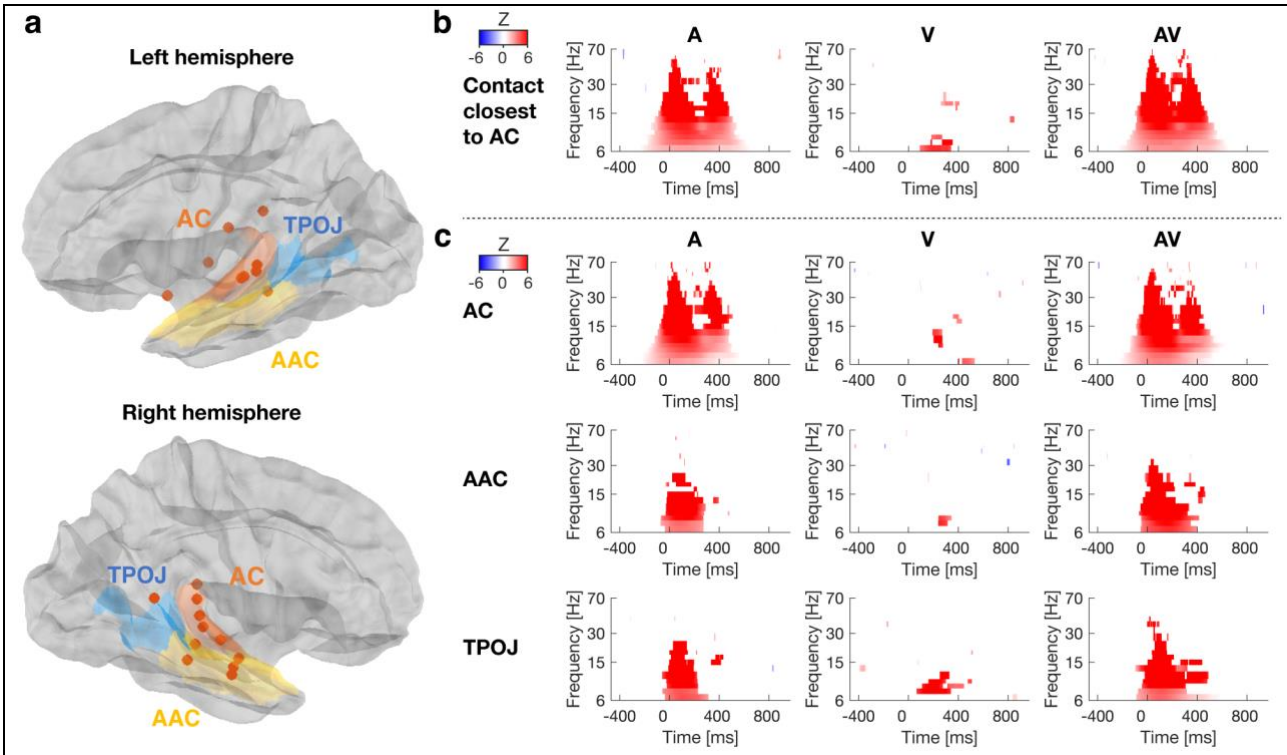

Fig. 6. Group analysis of ITPC. (**a**) Analysis sites in the standard brain representation. Each subject's SEEG contact closest to AC is marked with an orange dot. The orange, yellow, and blue labels show the HCP-based source-modeling ROIs. (**b**) Normalized ITPC in the electrode contact closest to AC. In addition to the strong ITPC effects to A and AV stimuli, there was also evidence of significant increase of low-frequency ITPC to V stimuli (FDR-adjusted $p<0.05$). These effects started less than 200 ms after the onset of the V stimulus. Most interestingly, the cross-sensory ITPC effect occurred in time/frequency windows where there was no evidence of power increases to V stimuli, in line with the hypothesis that cross-sensory influences could "entrain" intrinsic oscillations of AC [8]. (**c**) ROI-based group analysis of normalized ITPC values. In addition to responses to A and AV stimuli, there was evidence for significantly increased ITPC to V stimuli across the three ROIs. The data also show the expected early increases of ITPC to A and AV stimuli. Group averages of normalized ITPC values have been masked to time/frequency elements where the effects were statistically significant (FDR-adjusted $p<0.05$).

Experiment 2: Cross-sensory power changes in auditory cortex during complex stimulation and task

An important concern is whether the results described above, which were obtained during a simple task and basic stimuli, can be generalized to a more complex cognitive setting. Therefore, we analyzed data in a subgroup of 8 participants during additional lexical and non-lexical delayed match-to-sample tasks (DMS, **Fig. 7a**). The behavioral analysis suggested that the participants were able to perform according to the instruction. In the lexical and non-lexical DMS tasks, respectively, the mean ± SEM values of the PCR were 0.92 ± 0.04 and 0.96 ± 0.02. The respective RTs values were 1643 ± 347 ms and 1155 ± 179 ms.

Fig. 7 displays the results of a group analysis, which was conducted across contacts that in each participant were closest to AC, AAC, or TPOJ in both hemispheres. Consistent with the findings in the main experiment, we found no evidence of cross-sensory BHFA increases to symbolic V stimuli that were presented in either lexical or non-lexical contexts in AC, AAC, or TPOJ. At the same time, we observed a significant suppression of theta (<8 Hz) and beta (15-30 Hz) to visual stimuli in contacts closest to the left AC, AAC, and TPOJ. Interestingly, these cross-sensory effects were more obvious in the left than in the right hemisphere. Indices of predominantly left-lateralized effects were observed in in the BHFA measures in the higher areas ACC and TPOJ.

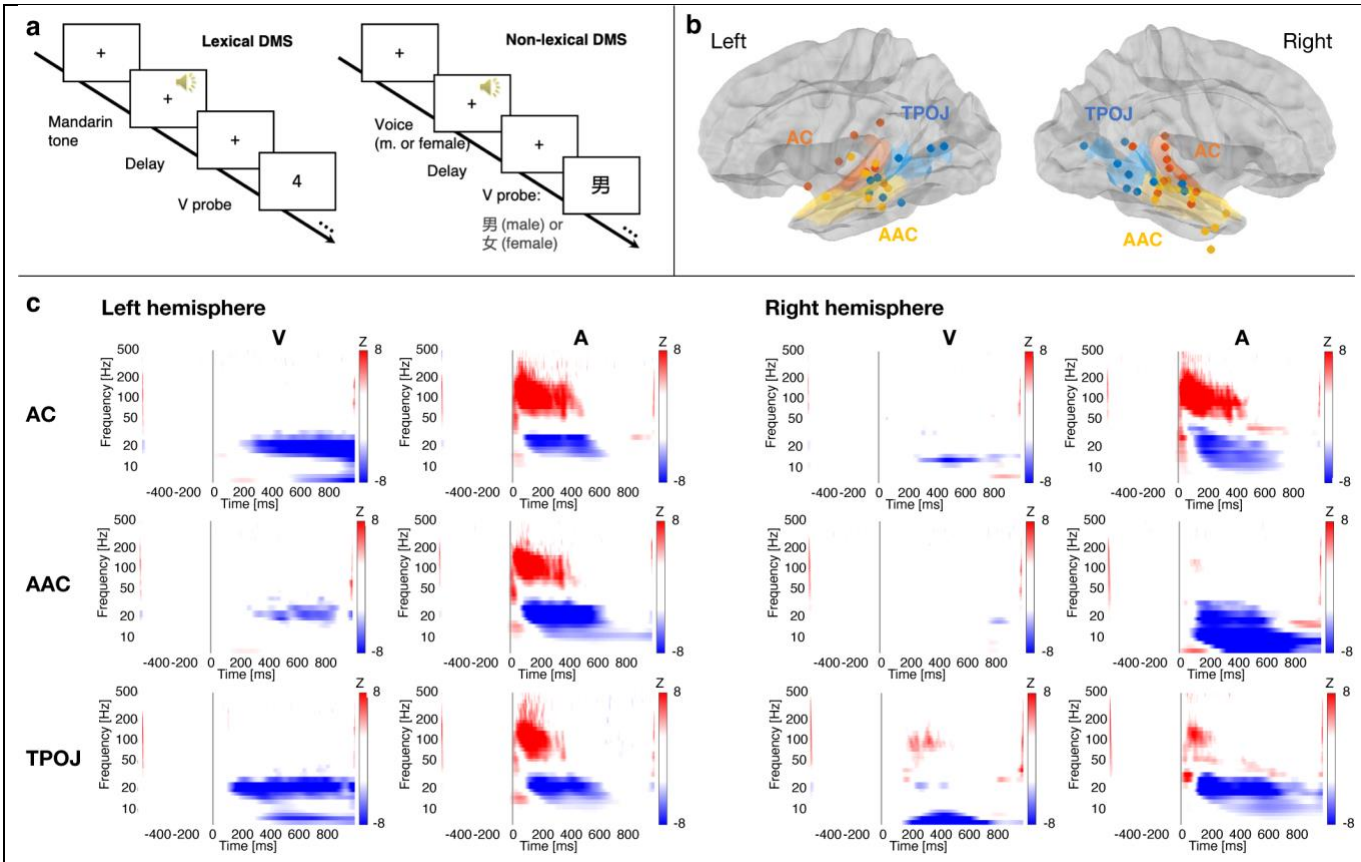

Figure 7. Group analysis of power in contacts closest to AC, AAC, and TPOJ in Experiment 2. (**a**) Delayed match-to-sample (DMS) tasks. In each trial of the lexical DMS task, the subjects were presented with an A stimulus, a male or female voice with one of four Mandarin tones, followed by a V probe, a number on the screen. Their task was to identify whether the V probe content matched the tone number of the A. In the non-lexical DMS task, the subjects were presented an A stimulus, a male or female voice, follwed by a V probe, a Mandarin symbol of male or female. Their task was to indicate whether the genders of the A item and V probe matched. (**b**) SEEG group analyses were conducted in contacts closest to AC, AAC, and TPOJ areas. (**c**) Group anaysis of power TFRs. Statistically significant BHFA (>70 Hz, FDR-adjusted p<0.05) emerged to A stimuli only. In the left hemisphere, cross-sensory symbolic V stimuli suppressed theta (<8 Hz) and beta (15-30 Hz) power, starting roughly 200-300 ms after stimulus onset. Interestingly, these cross-sensory V theta and beta suppression effects were less prominent in the right hemisphere.

Discussion

Here, we used direct intracranial depth-electrode recordings in 16 human participants to compare two competing theories of how cross-sensory influences take place in and near the AC. To minimize the account of higher semantic or linguistic feedback influences in our main experiment (*N*=16), we used simple noise-burst sounds and "checkerboard" visual stimuli that lack strong auditory associations. The results of the main experiment were compared to a cognitively more complex task, Experiment 2, in a subgroup of eight participants of the total cohort. In the frequency domain, visual stimuli modulated ITPC of low-frequency oscillations in AC without concurrent increases in signal power, suggesting cross-sensory phase resetting of intrinsic oscillatory activity [8]. Visual stimuli also resulted in a later beta-range ERDS effect in ACs. Similarity analyses of spatiotemporal patterns and our cross-correlation lag analyses between trial-averaged A and V responses provided further evidence of cross-sensory modulations of AC activity. However, no robust evidence of visually driven BHFA, a putative correlate of local neuronal firing [24-26], was found in ACs, to V visual stimuli with (Experiment 2) or without (main experiment) strong auditory-cognitive associations. No significant non-additive MSI effects (*i.e.*, AV ≠ A+V) [33] were found at the BHFA range either. MSI effects in ACs were concentrated at the beta range and below and these lower-frequency effects appeared to occur earlier in higher (TPOJ) than lower order (AC) areas along the auditory processing pathway.

The significant increase in ITPC, which resembles the results of an earlier subdural ECoG study in three human participants [22], could reflect transient modulations of the phase of intrinsic oscillations in AC. Evidence for this phenomenon was originally found in monkey studies of Peter Lakatos et al. [8] who investigated cross-sensory influences of somatosensory stimuli in primary AC. Lakatos et al. proposed that phase modulations, which occur without concurrent increases in the signal power, could be explained by phase resetting of ongoing intrinsic oscillations of AC. Such phase-resetting could, for example, help ensure that concurrent auditory inputs arrive to AC during at an optimal high-excitability phase, to amplify weak inputs during noisy listening conditions [8, 34, 35]. Support for this idea was provided by a recent intracranial EEG study, which suggested that AC neurons track the phase of visual speech and that this phase resetting amplifies the cortical representation of

speech signals [36]. In non-invasive human studies, cross-sensory phase resetting of AC oscillations has also been reported, e.g., after seeing lip movements [34] or conversational hand gestures [37]. What would make cross-sensory phase resetting a particularly relevant modulatory mechanism is that during normal communication the speakers facial and other gestured often slightly precede the onset of voice production.

BHFA signals are thought to reflect non-oscillatory broadband signals that correlate strongly with local neuronal firing [24-26], which offers a way to measure supra-threshold activation pattern in human SEEG [23] (for an alternative model, see, however, also [38]). Here, we mapped cross-sensory BHFA at the group level using a two-pronged strategy. First, BHFA was quantified from three anatomically normalized ROIs in each subject's surface-based cortical source estimates. Second, we analyzed BHFA in each subject's SEEG electrode contact that was closest to AC defined based on the HCP atlas. In the group analyses of source modeling data, traces of significant visually triggered BHFA signals, which were statistically significant in the FDR-adjusted estimates, were observed only in the area TPOJ. In contrast to the strong A and AV BHFA patterns, no significant visual BHFA effects were observed in AC, AAC, or the group analysis of the SEEG contact closest to AC. At the same time, in the exploratory, and statistically more liberal, uncorrected electrode-contact analysis in individual participants, significant BHFA to visual stimuli was observed in only one out of the 16 cases, in a participant whose sT contact closest to AC was, in fact, located in the upper bank of STS. These results are, overall, consistent with the observations in previous human ECoG [22] and SEEG studies [16] with smaller samples than in the present study of 16 participants. Taken together, these results suggest that at the population level, cross-sensory visual stimuli drive very weak, if any, suprathreshold neuronal activations in the vicinity of human AC.

The lack of cross-sensory BHFA in human AC is also in line with many previous studies that used more specific neurophysiological recordings in NHPs and other mammals. Laminar recordings suggested that cross-sensory somatosensory influences do not evoke increased MUA in the NHP primary AC [8]. Similar observation was reported in a subsequent NHP study where visual stimuli modulated single-unit activity (SUA) and MUA responses to auditory stimuli but did not trigger significantly increased firing when presented alone [6]. Our results are also consistent with the observations of Kajikawa et al. [30] who, further, concluded that even at the lower frequency range, most LFP responses reported in ACs to complex visual stimulus such as faces could largely

explainable by volume conduction from other areas. Opposite findings in NHP studies, which reported visually triggered firing effects in ACs have been attributed to byproducts of extensive training [17]. Beyond this, evidence for increases of suprathreshold activity by visual stimuli have been reported only in a small number of studies in other animal models [18, 20]. Our results are also broadly in line with previous human ECoG studies in the visual domain, which suggest very limited cross-sensory tactile BHFA effects even in higher-level visual areas of lateral occipital cortex [39]. All this is in line with the more conservative interpretation that cross-sensory stimuli play primarily a modulatory role in human sensory cortices including ACs.

In the power analysis, the most prominent effect of V stimuli in AC was the beta ERDS effect, which mimicked the ERDS effects following the intramodal A stimuli. An interesting perspective for interpreting these kinds of beta ERDS effects is offered by a recent intracranial SEEG study in humans, which compared oscillatory, BHFA, and multiunit firing activity effects elicited to A stimuli during sleep and wakefulness [40]. Interestingly, while the direct and indirect measures of neuronal activation were detectable at all levels of alertness, the beta ERDS was significantly suppressed during sleep. According to the interpretation of [40], the beta ERDS effect selective to the wakeful state reflects feedback influences necessary for conscious access to the incoming stimuli. Along these lines, it is possible that the present ERDS effects to V stimuli reflect crossmodal (or perhaps even non-specific or state-dependent [41]) influences on auditory cortex. Future studies for determining the exact role of this beta ERDS effect in crossmodal facilitation of detection of weak sounds are clearly warranted.

Previous human neuroimaging suggest V stimuli may not only enhance [4, 14], but also trigger anatomically selective reductions of blood oxygen level dependent (BOLD) responses in ACs [42, 43]. Similar crossmodal suppression effects, which can also be stimulus-content dependent, have been also evidenced in non-invasive studies using MEG and MEG [44-46]. These kinds of suppression effects have been proposed to reflect predictive coding, for example, when a content or location specific visual information becomes available slightly before the auditory stimulus [46] or in the event of anticipatory visual motion signals [47] (e.g., when a lip motion precedes the voice onset). One might thus speculate that the beta ERDS effect, which was observed for V stimuli alone and which seemed to be stronger for the AV than A events in AC (**Fig. 5c**), could reflect crossmodal or -sensory suppression of AC function. However, further studies are needed to elucidate this question, as in the

unimodal case, beta ERDS has been shown to correlate with enhanced rather than suppressed firing activity [31].

Potential routes for cross-sensory modulations and MSI effects in human AC have been previously proposed to include 1) feedback influences from higher-order attentional and/or polymodal association areas [34, 48], 2) direct inter-modal functional connectivity between low-level sensory areas [18, 49-51], and/or 3) subcortico-cortical feedback-type influences from non-specific thalamic nuclei to AC [52]. Many of the statistically strongest effects observed in the present study, including the beta-range ERDS and low-frequency MSI effects in AC, were found at relatively long latencies, that is, from more than 150-200 ms to up to 800 ms after the stimulus onset. Instead of multisensory processing, these kinds of effects could be explained by supramodal top-down influences [53] or even behavioral byproducts of the cross-sensory stimuli [41]. Furthermore, in the case of low-frequency MSIs, the earliest signs of statistically significant effects occurred in TPOJ rather than in AC. A major portion of cross-sensory and MSI effects observed in the frequency domain could thus be explained by feedback from higher areas. However, as estimated from the contact closest to AC, the cross-sensory ITPC effects were significant at the group level already ~ 100 ms after the stimulus onset. Furthermore, in our Laplacian-referenced LFP pattern analysis in the sT electrode, the cross-correlation analysis between LFP patterns to auditory vs. visual stimuli peaked at a lag of 55.2 ms, consistent with our previous MEG based estimate that cross-sensory visual responses follow the onset of auditory responses by about 55 ms [3]. These two last-mentioned observations leave room for an interpretation that more direct influences, based on direct cortico-cortical connectivity across different modalities or through subcortico-cortical influences via non-specific thalamic nuclei, play a role in cross-sensory modulation of human AC by simple stimuli. Naturally, what needs to be determined in future studies is to what extent this applies also to visual stimuli with strong auditory associations such as articulatory gestures.

In the classical sense, MSI refers to non-additive changes in the firing rates of individual neurons where the responses to bimodal audiovisual AV stimuli are stronger than the sum of the responses to auditory (A) and visual (V) stimuli alone [10]. In the present study, we however found evidence of significant MSI effects only in

low-frequency oscillations. A potential complication for interpreting these MSI effects is that they primarily occurred at time-frequency windows in which we observed a similar ERDS pattern for all three stimulus types.

An important consideration in evaluating the present results is that subthreshold modulation effects including low-frequency changes might be easier to detect than cross-sensory driving of neuronal activity. In the case of typical human studies, this is because non-invasive MEG and EEG, for example, detect only modulatory effects (which might also be true for fMRI). At the same time, even in intracranial recordings, detecting suprathreshold driving effects might be more limited because spiking could be more focal than modulatory effects in terms of the underlying neuronal tuning [for an AC example, see 54]. Due to their quadrupolar field pattern, spikes can be recorded at the immediate vicinity of the activated neuron. The detectability of BHFA, which was used here as a measure of driving effects, could be more limited because higher frequency signals have a shorter "coherence distance" than lower-frequency oscillations (a phenomenon often confused with "skull acting as a low-pass filter" in non-invasive studies). It is also worth noting that BHFA is correlate but not direct measure of underlying neuronal activity [23-26] (see also [38]). Nonetheless, as estimated by the group averages of baseline-normalized power to A stimuli, the effect sizes of individual subject's BHFA signals were at least as strong as, if not stronger, than effect sizes of lower-frequency effects that coincide the slow event-related responses observable in non-invasive EEG and MEG (**Fig. 4**).

In conclusion, we found direct intracranial neurophysiological evidence that cross-sensory visual stimuli modulate sub-threshold LFP signals and trigger low-frequency phase resetting in human ACs, with the cross-sensory LFP effects lagging those of unimodal A influences by about 50 ms. However, overall, in our large-sample study of intracranial human recordings, cross-sensory influences in ACs were somewhat weaker than we had anticipated. As determined using BHFA measures, there was little evidence of direct activation of AC by visual stimuli alone. Even when combined with concurrent A inputs, V stimuli drove only weak, if any, increases of BHFA effects in ACs themselves. Visually triggered BHFA influences were limited to the presumptively polymodal area TPOJ only. Finally, many of the most prominent cross-sensory modulatory influences, including the beta-range ERDS and concurrent MSI influences, occurred at relatively long latencies in ACs. Based on this, it seems that cross-sensory V inputs are involved in modulation of auditory responses, but no visual information

processing, per se, takes place in human ACs. Analogously to the effects of selective attention, such cross-sensory modulatory influences could help suppress irrelevant sound features [55], enhance task-relevant rhythmic inputs [8, 56], and help guide attentional feedback resources to appropriate points of time to enhance auditory speech perception [57].

Methods

Participants: We studied sixteen patients (15–45 years, seven women) with pharmacologically intractable epilepsy who were undergoing clinically indicated intracranial SEEG recordings. All aspects such as implantation and positioning of electrodes, as well as durations of recordings, were based purely on clinical needs. All patients gave written informed consent before participating in this study. The study was approved by the Institute Review Board Taipei Veteran General Hospital. The details of participants' demographics and electrode implantation plans are provided in **Supplementary Table S1**. The sample size was selected to exceed the numbers of participants, which were studied in previous comparable intracranial human ECoG [22] and SEEG studies [16].

Task and stimuli: In the main experiment, the 16 participants were presented auditory (A), visual (V), or audiovisual (AV) stimuli in a randomized order, at a 1.2–2.8 s jittered inter-stimulus interval (ISI; mean 2 s). In an oddball design, the participant was asked to press a button with their right index finger upon detecting a target stimulus (p=0.1) among the non-target stimuli (**Fig. 1**). In A trials, the non-target stimulus was a 300-ms white-noise burst and the target stimulus an equally long 440 Hz pure tone. In V trials, the non-target stimuli consisted of static checkerboard stimuli (3.5 x 3.5 degrees of visual angle, 300 ms duration) and the target was the same checkerboard but overlapped with a central black diamond pattern. In AV trials, the participant heard and saw the combinations of A and V stimuli; the AV target was the combination of pure tone and checkerboard with a black diamond. The onset of the V stimulus preceded the A onset by 48 ms. Two six-minute runs of data were collected from each patient. In total, the subject was presented with 100 A, 100 V, and 100 AV stimuli. Auditory stimuli were delivered binaurally via insert earphones (Model S14, Sensimetrics, Gloucester, MA, USA) and the visual stimuli on a 17-inch computer screen (Asus MM17; ASUSTeK Computer Inc, Taipei, Taiwan) positioned at a viewing distance of 60 cm, controlled by using E-Prime (Psychology Software Tools, Sharpsburg, PA, USA).

A subgroup of eight subjects (age, gender) participated also in a separate session with more complex task and stimuli than in the main experiment (**Fig. 7a**). This additional session was based on a delayed match-to-sample (DMS) design, with separate lexical and non-lexical parts. The SEEG data from the DMS tasks were analyzed together for the present purposes. In each trial of the Lexical DMS, the participant was first presented an auditory (A) stimulus item, a voice with one of four Mandarin tones. After a randomly jittering delay period of 1 to 1.5 s, the participant was shown a visual (V) probe, which contained one of the possible numbers (i.e., 1,3, 3, or 4) in the video screen. The participant was asked to press one button with their index finger if the content of the V probe matched with that of the A item. The task was self-paced, in other words, the task sequence moved on to the following trial only after the participant had responded. In each trial of the Non-lexical DMS, the participant was first presented an A stimulus, consisting of male or female voice stimulus. Then, after a jittering 1-1.5 s delay, the participant saw a V probe, consisting of the Mandarin symbol meaning "male" (i.e., 男） or "female" (i.e., 女）. Their task was to press one button with their index finger if the A voice and V symbol gender matched or another button with their middle finger if there was a mismatch.

Data acquisition: SEEG electrodes were placed solely based on the patient's clinical need, to identify epileptogenic zones. The patients were implanted with from 6 to 17 electrodes (0.3 mm diameter, 5-mm spacing; 6, 8, or 10 contacts per electrode Ad-Tech, Racine, WI, USA). SEEG data were collected at 2,048 samples/s. A white matter contact was used as a reference electrode in five of the 16 patients. In the remaining 11 patients, the scalp EEG electrode at the location FPz served as the initial reference [58-64]. However, in these 11 patients, the SEEG signals were re-referenced to a contact located in white matter before data analysis. **Figure 8a** depicts the distribution of all electrode contacts of all participants in a standard brain representation.

Two sets of anatomical MRIs were obtained, one before and another after each patient's electrode implantation surgery. We obtained pre-operative anatomical MRI images with a 3T MRI (Siemens Skyra, Siemens, Erlangen, Germany) using a MPRAGE sequence with TR/TI/TE/flip = 2530 ms/1100 ms/3.49 ms/7o, partition thickness = 1.33 mm, matrix = 256 x 256, 128 partitions, and FOV = 21 cm x 21 cm. The postoperative anatomical MRI was acquired at 1.5T (GE Signa HDxt system) with a fast spoiled gradient–recalled echo

sequence (TR/TE/TI 10.02/4.28/0 msec, flip angle 15°, matrix 256 * 256, bandwidth 31.2 kHz, view 256 × 256 mm, and axial slice thickness 1.0 mm).

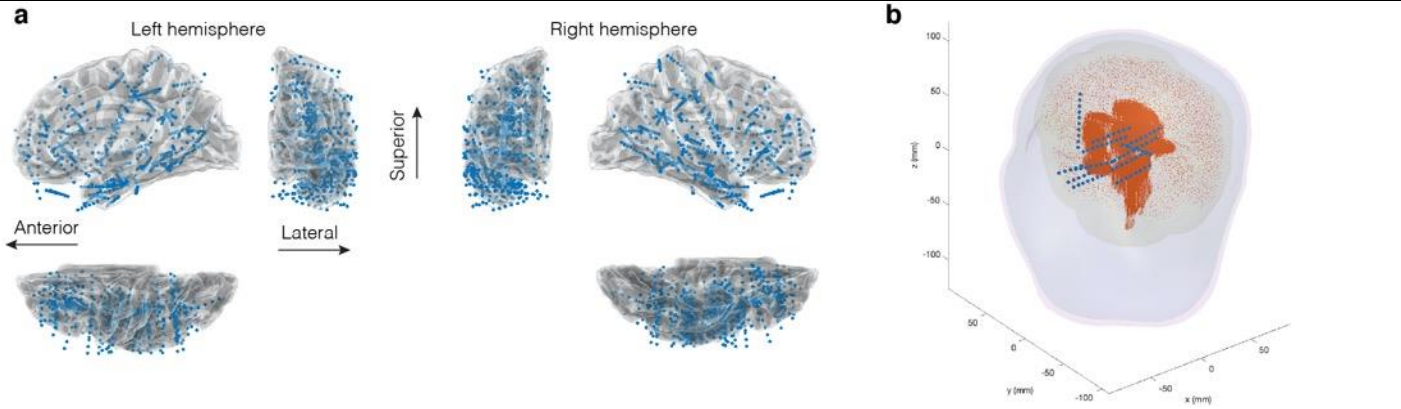

Figure 8. Electrode contact distribution and brain model diagram. (**a**) Locations of all electrode contacts, marked by the blue dots, are depicted in a template brain volume (MNI305). Lateral, frontal, and superior views of each hemisphere are shown. (**b**) A schematic of the source space (orange dots) including cortical and sub-cortical brain areas, locations of the electrode contacts (blue dots), and three anatomical boundaries (inner skull, outer skull, and outer scalp) for the lead field calculation using Boundary Element Model in a representative participant.

Preprocessing: SEEG preprocessing was performed by using the Matlab (MathWorks, Natick, MA) EEGLAB toolbox (version 14.1.0; http://sccn.ucsd.edu/eeglab/). Electrode contacts that carried excessive line noise were excluded from the analyses based on visual inspection. These analyses also excluded electrode contacts within epileptic lesion sites according to the neurologists (authors H.Y.Y., C.C.C.). SEEG waveforms were notch filtered at 60 Hz to reduce power line artifacts and detrended when cropping the raw data into trials. Trials including epileptiform activity were excluded. SEEG recording was then segmented into epochs of 1500 ms duration with a 500-ms pre-stimulus baseline relative to the A, V, and AV stimulus onsets. SEEG epochs with deflections larger than six standard deviations from the epoch average were discarded. TFR power and ITPC analyses were based on individual trials. The event-related response analyses in Figs. 2-3 utilize trial-averaged responses.

Source modeling: The coverage provided by depth electrode contacts is sparse and, due to clinical reasons, differs between patients. These two complications make it very difficult to analyze the extent of activations within any individual subjects and to conduct anatomically normalized group analyses, respectively. These problems

could potentially be circumvented by intracranial source modeling of the SEEG data. Although SEEG source modeling has the same mathematical limitations associated with ill-posed inverse problems as MEG/EEG source modeling, a crucial benefit is the directly measured depth information of the origins of the signals within the brain parenchyma. Another point is that the BHFA signal that is measurable with SEEG, and which is not visible to non-invasive MEG/EEG, has been reported to be highly focal [24, 26]. Therefore, in addition to conventional signal analyses, we employed inverse modeling of the intracranial source currents to facilitate anatomically normalized group analyses of cross-sensory influences on human AC.

SEEG source modeling was conducted using our recently published strategy [28]. The locations of electrode contacts in the individual's brain were identified from the post-surgery MRI, based on discrete dark image voxel clusters caused by the susceptibility artifact at each electrode contact. After specifying the distances between neighboring contacts and the number of contacts in an electrode, the electrode was manually aligned with the dark image voxel clusters in the post-surgery MRI using our in-house Matlab (Mathworks Inc., Natick MA, USA) software with a graphical user interface. Thereafter, contact locations were further optimized (within ±10 mm translation and ±2-degree rotation) by minimizing the sum of squares of image voxel values at all contact locations and their neighboring voxels within a 3x3x3 voxel cube in the post-surgery MRI using the Matlab *patternsearch* function. The SEEG electrode contact locations were then registered to the pre-surgery MRI, which was used to build Boundary Element Models (BEM's) required for the lead field calculation and to define locations of potential neural current sources. The inner-skull, outer-skull, and outer-scalp surfaces for the BEMs, as well as the cortical source spaces at the gray/white matter boundaries and sub-cortical source spaces, including thalamus, caudate, putamen, hippocampus, amygdala, and brain stem, were automatically reconstructed from the pre-surgery MRI by using FreeSurfer (http://surfer.nmr.mgh.harvard.edu). In each cortical source location, which were separated by about 5 mm from one another, we had three orthogonal neural current dipoles in +*x*, +*y*, and +*z* directions. An example of the current source space electrode contacts, as well as of the inner-skull, outer-skull, and outer-scalp surfaces from a representative patient are shown in **Figure 8b**. The lead fields were calculated by using the *OpenMEEG* package (https://openmeeg.github.io/) [65, 66], with the relative conductivity values for air, scalp, brain parenchyma, and skull being 0, 1, 1, and 0.0125, respectively.

The measured sEEG data and the cortical current sources at time t are related to each other by $\mathbf{y}(t) = \mathbf{A}\,\mathbf{x}(t) + \mathbf{n}(t)$, where $\mathbf{y}(t)$ denotes the collection of sEEG data across electrode contacts, $\mathbf{x}(t)$ denotes the unknown current strength, and $\mathbf{n}(t)$ denotes noise. Electrode contacts potentially related to epileptic activity were excluded. The $\mathbf{x}(t)$ has 3 x m elements to describe the currents in three orthogonal directions at m brain locations and $\mathbf{A}$ is the lead field matrix. For a unit current dipole source at location $\mathbf{r'}$ in the $+x$, $+y$, or $+z$ direction, the electric potentials measured from all electrode contacts are reflected by $\mathbf{a}(\mathbf{r'}) = [\mathbf{a}_x(\mathbf{r'}), \mathbf{a}_y(\mathbf{r'}), \mathbf{a}_z(\mathbf{r'})]$. Assembling $\mathbf{a}(\mathbf{r'})$ across all possible current source locations created the lead field matrix $\mathbf{A}$: $\mathbf{A} = [\mathbf{a}(\mathbf{r'}_1), \mathbf{a}(\mathbf{r'}_2), \ldots, \mathbf{a}(\mathbf{r'}_k)]$, $k = 1, \ldots, d$ where d denotes the total number of current dipole source locations.

To estimate $\mathbf{x}(t)$ using the minimum-norm estimate (MNE), we had $\boldsymbol{x}_{MNE}(t) = \boldsymbol{R}\boldsymbol{A}^T(\boldsymbol{A}\boldsymbol{R}\boldsymbol{A}^T + \lambda\boldsymbol{C})^{-1}\boldsymbol{y}(t)$, where $\mathbf{C}$ was the noise covariance matrix $\boldsymbol{C} = \langle \boldsymbol{n}(t)\boldsymbol{n}^{\boldsymbol{T}}(t)\rangle$. The operator $\langle\cdot\rangle$ takes the ensemble average across the pre-stimulus interval (-200 ms to 0) with data concatenated across trials. The regularization λ tuned the balance between the strength of the estimated neuronal current strength and the discrepancy between the modeled and measured data. We chose $\lambda = 10$ [67].

Regions of Interest (ROI): Three ROIs were defined based on the Human Connectome Project (HCP) multimodal parcellation (MMP1) atlas, combined version [68], which was projected to the Freesurfer "fsaverage" standard brain surface representation. From the HCP atlas, we selected the ROIs "early auditory cortex" (AC), "auditory association cortex" (AAC), and "temporo-parieto-occipital junction" (TPOJ), which were subsequently resampled to each participant's individual cortical surface representation. For the group and individual-level TFR analyses, in each subject, we determined the contact that was closest to the HCP labels AC, AAC, and TPOJ. In the source modeling analysis of SEEG data, single-trial MNE time courses were calculated for the x, y, and z components at each dipole location and averaged across each ROI.

Time-frequency decomposition: Time-frequency representations (TFR) of SEEG power were calculated in Matlab by convolving individual trials with a dictionary of 7-cycle Morlet wavelets. In the case of ROIs of source estimates, the power TFRs were determined from the sums of squares of the amplitude values along three orthogonal dipole directions. For the group analyses, the power values were then averaged across trials and baseline normalized. In the supplementary individual-level analysis, we compared the power at each

time/frequency element after the stimulus onset to the mean power during the respective pre-stimulus baseline period using paired t-tests. The inter-trial phase consistency (ITPC) across trials was calculated by dividing the mean amplitudes of the wavelet coefficients across the trials by the mean of absolute values of the amplitudes: $ITPC(f,t) = \frac{|\sum W(f,t)_m|}{\sum |W(f,t)_m|}$ where W denotes the wavelet coefficient, f is frequency, t is time, and m is the trial number.

Cross-correlation analysis of the lag between V and A responses. Timing differences between responses to A vs. V stimuli were evaluated using a cross-correlation analysis. This analysis was conducted using a bipolar reference, in a contact that demonstrated both A and V activity that exceeded the amplitude of pre-stimulus baseline noise (**Supplementary Figs. 1-3**). In each participant, we computed cross-correlations between the absolute values of A and V responses 0-300 ms after the stimulus onset (*i.e.*, xcorr(abs(A),abs(V)), maximum lag 300 ms; *xcorr.m*, Matlab, Natick, MA). Given the strong a priori hypothesis that V responses, if any, would lag rather than lead responses to A stimuli, we concentrated the statistical analysis on the positive side of the correlogram where positive cross-values between abs(A) and abs(V) signals reflect V lagging A. In line with the conventional approach (*e.g.*, the Matlab built in function *finddelay.m*), the lag was considered to correspond the local maximum of the cross-correlation within this range.

Spatiotemporal pattern similarity analysis of superior temporal SEEG data. We compared the similarity of event-related signals elicited by A and V stimuli by using 1,500 ms SEEG epochs, including a 500 ms pre-stimulus baseline period, averaged across trials from Laplacian-referenced contacts of the sT electrode. In other words, in each electrode with *n* time point samples and *m* contacts, each signal in the contacts 2...*m*-1 was referred to the average of signals of its immediate neighbors by elementwise subtraction, resulting in an $n\times(m-2)$ matrix of Laplacian-referenced SEEG traces per electrode. Only subjects with more than four adjacent contacts with acceptable signal quality in the sT electrode were included in this analysis (13 of the 16 participants). We estimate the spatiotemporal pattern similarity between A and V conditions in sliding 300 ms time windows, corresponding to 605 time-point samples at our 2048 Hz sampling rate, before and after the stimulus. In each time window, the task condition and subject-specific slicing $B_{605\times(m-2)}$ matrices were reshaped to their respective vectors b_A and b_V with $605\times(m-2)$ elements. Within each subject, Fisher-transformed Kendall

correlation coefficients were then calculated for each time window (**Fig. 3b**). A maximum-statistic non-parametric permutation procedure was utilized to determine the statistical significance of the group-average of pattern similarity measures: In 500 permutations, we recalculated the correlations for each time window, after randomly shuffled the order of the contacts and the timepoints. That is, the randomization was conducted along the appropriate exchangeability blocks of the $B_{605\times(m-2)}$ matrix before it was reshaped to the vectors b_A and b_V for calculating the correlation. Finally, to handle multiple comparisons, we selected the maximum group average across all time windows from each permutation, to be entered to the null distribution for determining the critical value (**Fig. 3b**).

Group statistics. In the behavioral analysis, we compared RTs and PCRs between AV and A, as well as between AV and V conditions using paired t-tests, corrected for multiple comparisons using the Bonferroni correction (total number of tests = 4). TFR values at each frequency were averaged across trials, baseline normalized, and taking the 10-based logarithm. Because the ITPC values are bounded within the range between 0 and 1, the values were transformed to Z-score-like values using the Rayleigh test and norminv.m of Matlab [70]. We used a linear mixed effect (LME) model to calculate the statistical inferences of TFR and ITPC in A, V, and AV across patients in both electrode and source analysis using the fitlme.m function of Matlab (Mathworks, Natick, MA). For each condition, the analysis was conducted each element of the relevant time-frequency grid. To compare each task condition separately against the baseline, we used LME models defined by the formula (Wilkinson notation, [71]) $M \sim 1 + (1|subject_id)$ where the M is the to-be-predicted effect (signal power or ITPC value, respectively), 1 refers to the fixed effect of the intercept, and the term (1|subject_id) refers to the random effect (i.e., random intercept) of the subject identity. Here, the statistical significance was determined based on the fixed effect of intercept. For the contrast between AV and other conditions, we first calculated the to-be-predicted effect size of the contrast of interest, which was then predicted by the same model. All comparisons were corrected for the inflation of type-I error by controlling the false discovery rate (FDR) across the time-frequency elements.

The group TFR analysis of Experiment 2 was conducted in the contacts closest to the ROIs representing AC, AAC, and TPOJ, separately for all A item trials and V probe epochs. In this analysis, the A and V epoch data from Lexical and Non-lexical DSM tasks were pooled together.

Data for reference.

Codes used for this study are open to access at https://github.com/fahsuanlin/fhlin_toolbox/wiki.

Deidentified data utilized to yield our main results are available at https://dataverse.harvard.edu/privateurl.xhtml?token=d7216368-34bf-4a8a-858a-824b216385fb.

Any additional information required to reanalyze the data reported in this paper is available from the Corresponding Author.

Acknowledgements

Supported by: R01DC017991, R01DC016765, R01DC016915; Acad. Finland 276643, 298131, 308431. Russian Science Foundation 22-48-08002.

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