

Appendix for
Multichannel optical cochlear implants enable spectrally distinct auditory activity
Albrecht et al.

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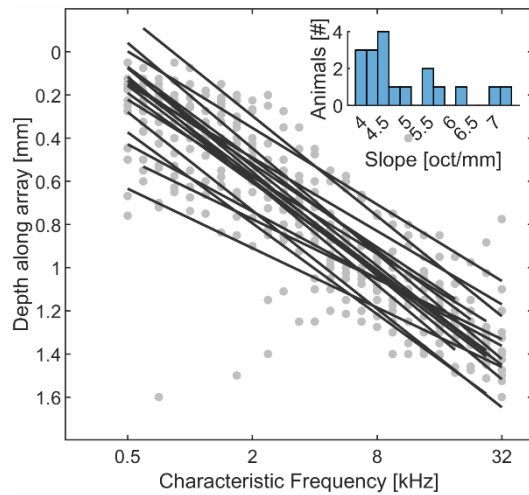
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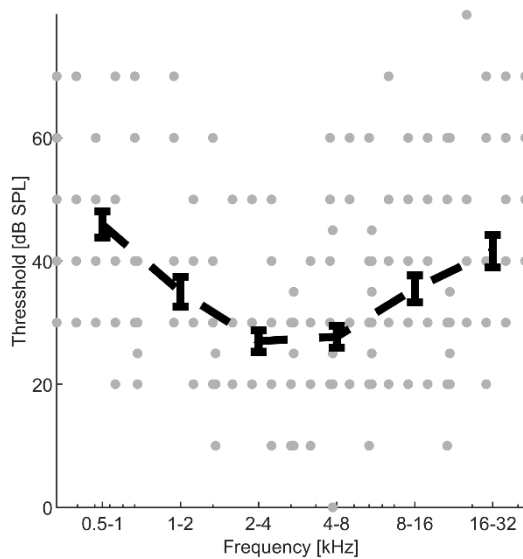
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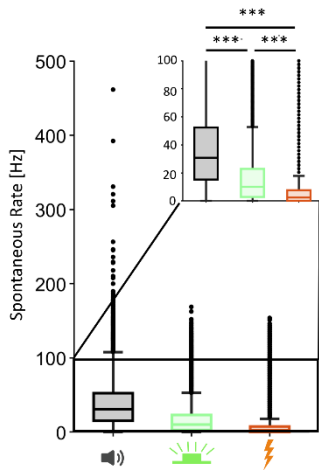


Appendix Figure S1. Placement of the recording array along the tonotopic axis of the ICC. Depth of the best electrode for the presented sound frequencies relative to the most dorsal recording electrode. Tonotopic slopes were estimated by linear fits for each animal after outlier removal ($n = 9$ non-injected and $n = 8$ ChReef-injected animals). The inset axis shows the distribution of tonotopic slopes across animals.

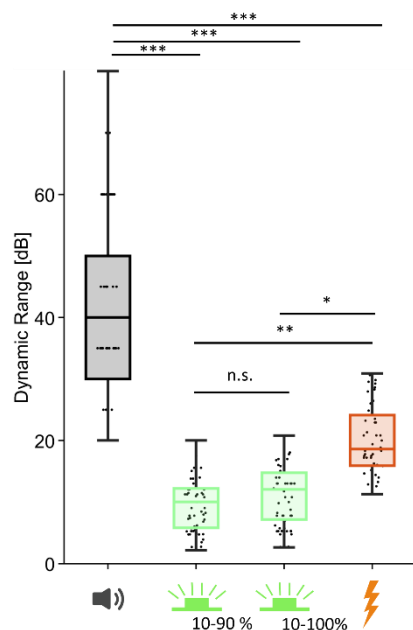


Appendix Figure S2. Thresholds for ICC activation by pure tones.

Threshold of ICC activation by pure tones of different frequencies in non-injected animals, defined as the first stimulation intensity to elicit a $d' \geq 1$. Values were binned by frequency at a width of one octave (mean $\pm$ SEM).

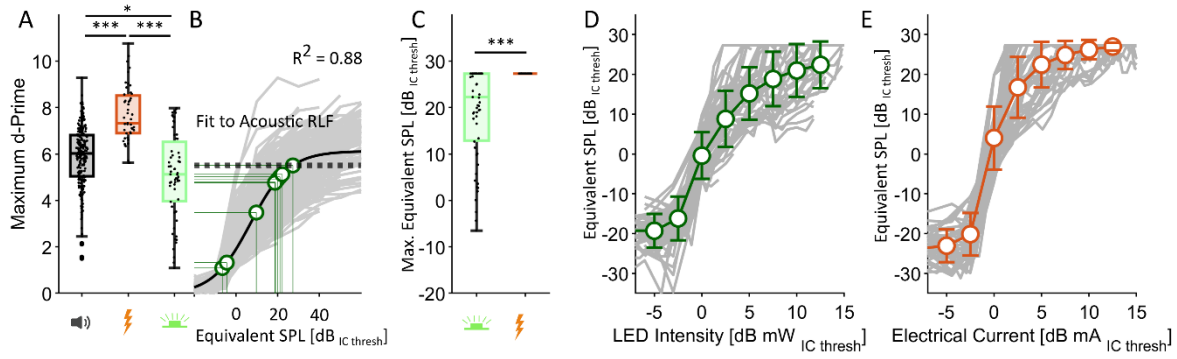


Appendix Figure S3. Spontaneous ICC activity across stimulation-modality groups. Spontaneous firing rates recorded in the ICC from ChReef-injected animals used for optical stimulation ($n = 8$), non-injected animals used for acoustic stimulation ($n = 9$), and non-injected animals used for electrical stimulation ($n = 12$). Each data point represents one recording. Groups were compared using a Kruskal–Wallis test followed by Dunn’s multiple-comparisons test. Box plots indicate quartiles and medians; whiskers extend to minimum and maximum values. Acoustic data are shown in black, optical in green, and electrical in red. Icons were created in BioRender (see Fig. 2).



Appendix Figure S4. Effect of analysis method on dynamic-range estimates.

Distribution of dynamic ranges for acoustic, optical and electrical stimulation. For optical stimulation, the dynamic range was additionally estimated as the intensity range required to increase firing rates from 10% to 100% of the maximum firing rate. Acoustic data are shown in black, optical in green, and electrical in red. Icons were created in BioRender (see Fig. 2).



Appendix Figure S5. Estimation of an equivalent SPL by d-Prime-Analysis.

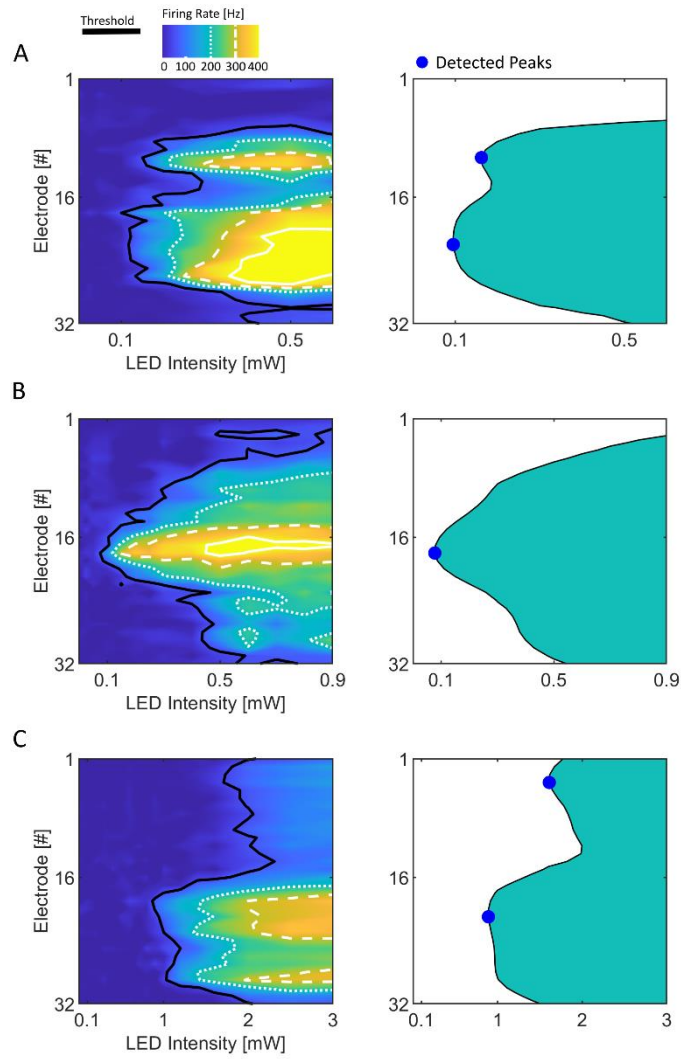
(A) Distribution of the maximum cumulative d-Prime achieved by acoustic, optical, and electrical stimulation.

(B) Quantification of an equivalent sound pressure level (SPL) for optical and electrical stimulation. A sigmoid fit to the dPrime-level function for acoustic stimulation (Fig. S7) (pseudo- $R^2 = 0.88$) was used as a reference to map firing rates elicited by optical and electrical stimulation onto an equivalent SPL.

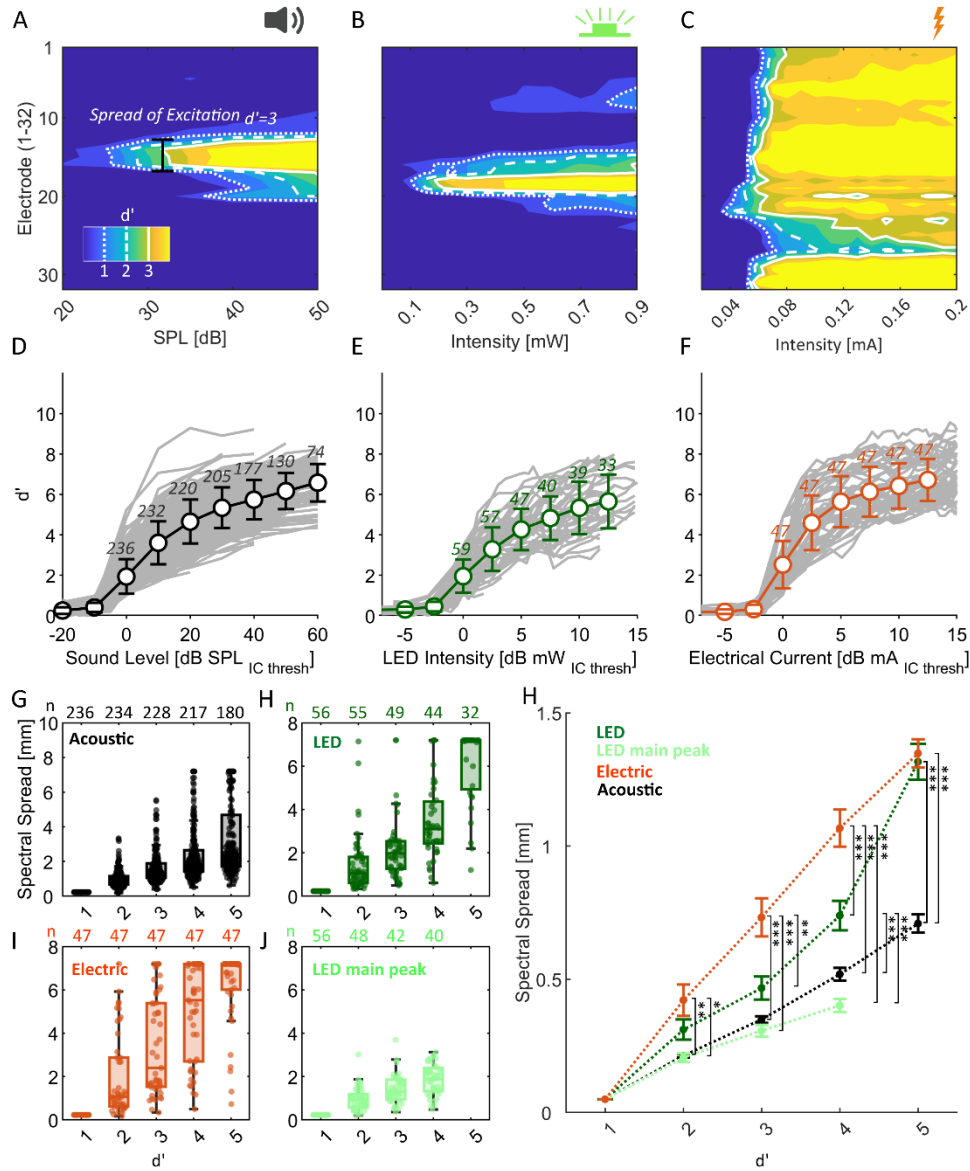
(C) Comparison of the maximum equivalent SPL, derived from the mapping in panel B, achieved by optical and electrical stimulation.

(D-E) Mapping of evoked firing rates achieved by optical (J) and electrical stimulation (K) to an equivalent SPL (mean $\pm$ SD). The data shown in Fig. S7D-F was mapped onto the dPrime-level function for acoustic stimulation as shown in B. Traces for individual recordings are shown in the background. The number of recordings contributing to each data point corresponds to the values shown in Fig. S7D

Statistical significance is indicated by stars (*p < 0.05, **p < 0.01, ***p < 0.001), based on Kruskal-Wallis test with Tukey's post-hoc pairwise comparison. Boxes in A and C indicate quartiles and median, with whiskers extending to the minimum and maximum values. Icons in A and C were created in BioRender (see. Fig. 2).



Appendix Figure S6. Automated spectral-peak detection method. (A–C) Threshold contours of STCs obtained with single-LED stimulation are shown before smoothing in the left column and after smoothing with a two-dimensional Gaussian window in the right column. Smoothing was applied to reduce over-detection of noise-related peaks. Remaining peaks were automatically detected using MATLAB’s *findpeaks* function and are indicated by blue dots.



Appendix Figure S7. Alternative estimation of spectral spread of cochlear excitation by cumulative d-Prime-Analysis.

(A-C) D-Prime-based STCs for sound, light and electrical stimulation. Quantification of spectral spread in different stimulation modalities: Spread of excitation (SoE) is measured as the width of the STC at different activation levels quantified as the highest cumulative d-Prime in response to a given stimulus (example shown for $d'=3$ in Panel A). Icons were created in BioRender (see. Fig. 2).

(D-F) Cumulative d-Prime quantified using the maximally responding electrode at each stimulus intensity (mean $\pm$ SD) for acoustic (D), optical (E), and electrical (F) stimulation. Traces for individual recordings are plotted in the background. The number of recordings contributing to each data point is indicated.

(G-J) Spectral Spread at different d-Prime-Levels for acoustic (D), optical (E) and electrical (F) stimulation. For optical stimulation the spectral spread was additionally quantified while excluding any secondary spectral peaks. The number of data points contributing to at each activation level is indicated above each panel.

(K) Comparison of spectral spread (Mean $\pm$ SEM) for different stimulus modalities i.e. sound, light and electrical stimulation as shown in D-G. Statistical comparisons were conducted using a linear mixed-effects model, with animal treated as a random factor and activation level and spectral spread treated as fixed effects. (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Only significant differences are indicated

Appendix Tables

Linear mixed-effects model coefficients for spectral spread

Model: SoE [oct] ~ 1 + FR*modality + (1 | subject)

Effect	β	SE	t	p
Intercept	1.48	0.40	3.69	2.3E-04

Main effects: Evoked Firing Rate (FR, 100 Hz reference)

150 Hz	0.61	0.20	3.05	2.3E-03
200 Hz	1.17	0.20	5.72	1.2E-08
250 Hz	2.48	0.21	12.08	1.6E-32
300 Hz	3.47	0.21	16.27	5.3E-56
350 Hz	4.48	0.23	19.75	1.6E-79

Main effects: Modality (LED reference)

acoustic	-1.21	0.55	-2.18	2.9E-02
electric	0.65	0.53	1.24	2.2E-01
LED_main_peak	-0.23	0.20	-1.16	2.5E-01

Interactions: Modality x Firing Rate

150 Hz x acoustic	-0.16	0.23	-0.72	4.7E-01
200 Hz x acoustic	-0.43	0.23	-1.88	6.0E-02
250 Hz x acoustic	-1.44	0.23	-6.25	5.1E-10
300 Hz x acoustic	-2.14	0.24	-8.96	7.3E-19
350 Hz x acoustic	-2.80	0.25	-11.15	4.7E-28
150 Hz x electric	1.03	0.29	3.56	3.8E-04
200 Hz x electric	1.58	0.29	5.38	8.1E-08
250 Hz x electric	1.44	0.29	4.89	1.1E-06
300 Hz x electric	1.24	0.30	4.09	4.5E-05
350 Hz x electric	0.57	0.32	1.77	7.7E-02
150 Hz x LED main peak	-0.03	0.29	-0.09	9.3E-01
200 Hz x LED main peak	0.02	0.30	0.07	9.5E-01
250 Hz x LED main peak	-1.03	0.31	-3.28	1.0E-03
300 Hz x LED main peak	-1.56	0.34	-4.54	6.0E-06
350 Hz x LED main peak	-2.29	0.42	-5.43	6.2E-08

Random effects:

subject intercept variance = 1.13;

residual variance = 1.05

Appendix Table S1. Linear mixed-effects model coefficients for spectral spread.

Fixed-effect estimates from the linear mixed-effects model predicting spread of excitation (SoE) from firing rate (FR), modality, and their interaction (Fig. 6H). Modality was coded with LED as the reference category.

Abbreviations: β , coefficient estimate; SE, standard error; t, t-statistic. Subjects correspond to individual animals.

Model fit performance of representational dissimilarity across modalities as a function of stimulus spacing (Fig. EV 3)
Model (LME):

RD $\sim$ 1 + modality * centered log2 stimulus spacing + (1 | subject)
+ (1 + centered log stimulus spacing | subject)

Firing Rate [Hz]	Modality	RMSE	R ²
100	Acoustic	0.21	0.73
	Optic	0.17	0.72
	Electric	0.16	0.78
150	Acoustic	0.21	0.73
	Optic	0.17	0.81
	Electric	0.14	0.83
200	Acoustic	0.22	0.68
	Optic	0.22	0.79
	Electric	0.14	0.86
250	Acoustic	0.20	0.73
	Optic	0.24	0.77
	Electric	0.14	0.87
300	Acoustic	0.19	0.72
	Optic	0.16	0.83
	Electric	0.14	0.87
350	Acoustic	0.20	0.64
	Optic	0.20	0.68
	Electric	0.15	0.88
400	Acoustic	0.13	0.64
	Optic	0.11	0.62
	Electric	0.15	0.87

Appendix Table S2. Model fit performance of representational dissimilarity across modalities and stimulus spacing.

Prediction performance metrics (RMSE and R²) for the linear mixed-effects models of representational dissimilarity (RD) across stimulus spacing and modalities (Fig. EV3). Models were fitted separately for each activation level (evoked firing rate).

Abbreviations: RD, representational dissimilarity; RMSE, root mean squared error; R², coefficient of determination.

Model fit performance of representational dissimilarity across modalities as a function of stimulus spacing and activation level (Fig. 7)

Model (LME):

RD ~ 1 + mod*FR
+ mod x centered log2 stimulus spacing (logspacing_c)
+ activation x logspacing_c
+ mod:activation x logspacing_c
+ (1 | subject)
+ (1 + logspacing_c | subject)

Modality	RMSE	R ²
Acoustic	0.21	0.67
Optic	0.25	0.63
Electric	0.15	0.83

Appendix Table S3. Model fit performance of representational dissimilarity across modalities, stimulus spacing and activation level.

Prediction performance metrics (RMSE and R²) for the linear mixed-effects model of representational dissimilarity (RD) across stimulus spacing, modalities and activation level (Fig. 8).

Abbreviations: RD, representational dissimilarity; centered log2 stimulus spacing, logspacing_c; mod, modality; RMSE, root mean squared error; R², coefficient of determination.

Censored values per modality for estimation of stimulus spacing at the neurometric threshold (Fig. 8)

Acoustic



Evoked Firing Rate [Hz]	Animal count	Upward censored	Downward censored	Uncensored
100	8	12.50%	25.00%	62.50%
150	8	0.00%	62.50%	37.50%
200	8	0.00%	62.50%	37.50%
250	8	0.00%	37.50%	62.50%
300	8	0.00%	37.50%	62.50%
350	8	0.00%	25.00%	75.00%
400	8	0.00%	12.50%	87.50%

Optical



Evoked Firing Rate [Hz]	Animal count	Upward censored	Downward censored	Uncensored
100	8	0.00%	0.00%	100.00%
150	7	0.00%	0.00%	100.00%
200	7	14.29%	14.29%	71.43%
250	7	14.29%	0.00%	85.71%
300	7	14.29%	0.00%	85.71%
350	6	16.67%	16.67%	66.67%
400	5	20.00%	20.00%	60.00%

Electrical



Evoked Firing Rate [Hz]	Animal count	Upward censored	Downward censored	Uncensored
100	12	0.00%	75.00%	25.00%
150	12	8.33%	58.33%	33.33%
200	12	8.33%	41.67%	50.00%
250	12	41.67%	25.00%	33.33%
300	11	36.36%	27.27%	36.36%
350	10	50.00%	10.00%	40.00%
400	6	66.67%	0.00%	33.33%

Appendix Table S4. Censored values per modality for estimation of stimulus spacing at the neurometric threshold.

For estimation of the minimum stimulus spacing required to reach the neurometric threshold, values exceeding the upper or lower bounds of the sampled spacing range were censored to

the maximum or minimum measured values, respectively (Fig. 8I). Icons were created in BioRender (see **Fig. 2**).

Linear mixed-effects model coefficients for spacing at neurometric threshold

Model: Spacing at Threshold [mm] ~ 1 + ER * modality + (1 | subject)

Effect	β	SE	t	p
Intercept	1.55	0.19	8.05	1.89E-13

Main effects: Evoked Firing Rate (ER, 100 Hz reference)

150 Hz	-1.18	0.24	-4.92	2.14E-06
200 Hz	-1.40	0.24	-5.88	2.43E-08
250 Hz	-1.36	0.24	-5.68	6.43E-08
300 Hz	-1.34	0.24	-5.60	9.41E-08
350 Hz	-1.33	0.24	-5.55	1.16E-07
400 Hz	-1.28	0.24	-5.37	2.73E-07

Main effects: Modality (acoustic reference)

LED	-0.73	0.27	-2.66	8.55E-03
electric	-0.91	0.25	-3.67	3.32E-04

Interactions: Modality x Firing Rate

1.05	0.35	3.06	1.05	2.63E-03
1.23	0.35	3.57	1.23	4.74E-04
1.20	0.35	3.47	1.20	6.67E-04
1.13	0.35	3.27	1.13	1.32E-03
1.13	0.35	3.19	1.13	1.73E-03
1.23	0.37	3.38	1.23	9.16E-04
1.29	0.31	4.18	1.29	4.76E-05
1.69	0.31	5.48	1.69	1.67E-07
1.85	0.31	6.00	1.85	1.31E-08
1.84	0.31	5.92	1.84	1.96E-08
2.12	0.32	6.73	2.12	3.04E-10
2.23	0.34	6.55	2.23	7.67E-10

Random effects:

subject intercept variance = 0.07; residual variance = 0.23

Appendix Table S5. Linear mixed-effects model coefficients for spacing at neurometric threshold.

Fixed-effect estimates from the linear mixed-effects model predicting the spacing at the neurometric threshold from evoked firing rate (FR), modality, and their interaction (Fig. 8I). Modality was coded with acoustics as the reference category.

Abbreviations: β , coefficient estimate; SE, standard error; t, t-statistic. Subjects correspond to individual animals.

Appendix Methods

Quantification of response strength and spectral spread using d' -Analysis

To enable comparison with previous studies, we additionally quantified ICC responses using cumulative d' analysis, a measure derived from signal detection theory (Macmillan and Creelman, 2004). For the main figures, however, we used evoked firing rate to quantify response strength, because this allowed direct comparison to rate-level functions across modalities and avoided potential bias arising from differences in inter-trial variability between stimulus conditions.

Responses obtained from 30 repetitions at each stimulus intensity were used to calculate cumulative d' values (Macmillan and Creelman, 2004; Middlebrooks and Snyder, 2007). For each recording site, firing-rate distributions evoked at successive stimulus intensities were used to construct empirical receiver operating characteristic (ROC) curves, from which the corresponding areas under the curve (AUC) were obtained. d' values were then derived from the AUC using the inverse cumulative normal distribution and summed cumulatively across increasing stimulus intensities to yield the cumulative d' value. The spatial distribution of cumulative d' values across recording sites was visualized by drawing iso-contour lines at defined d' levels ($d' = 1, 2$, and 3) using MATLAB's built-in `contourf` function.

To compare the spread of excitation in this framework, we measured the width of the STC constructed from d' -contours at matched activation levels (Dieter et al., 2019; Keppeler et al., 2020). For each activation level, the corresponding stimulus intensity was defined as the lowest intensity at which a given d' -contour ($d' = 1-5$) was reached. STC width was then measured as the distance between the most dorsal and ventral intersections of the $d'=1$ -contour at that intensity.