Supplemental information

Sequential transmission of task-relevant information in cortical neuronal networks

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Supplemental Figures S1-S6
Supplemental Tables S1-S6
**Supplemental Figure S1.** Time-course of $SI$, $CI$, and $II$ averaged over neurons that carried stimulus information ($SI$) only in A-B and choice information ($CI$) only in C-D. Related to Figure 3. As in Figure 3, we quantified the $SI$, $CI$, and $II$ in six separate stages of the behavioral task, which account for the peri-stimulus (0-1.5 s) and the post-stimulus intervals (1.5-3 s) shown by the shaded regions. Error bars show one standard error of the mean (SEM; $n$=#neurons with $SI$, $CI$ peaks within the stage).
Supplemental Figure S2. Two neurons having II is neither necessary nor sufficient for them to be GC-linked. Related to Figure 4. A. The first case shows two II neurons, i.e. two neurons that are modulated by stimulus signal and both modulate a choice signal. However, they do not modulate each other’s activity and hence there is no GC link. B. The second case shows two neurons in which the activity of neuron 1 is modulated by the activity of neuron 2, i.e. there is a GC link from neuron 2 to neuron 1. However, neither neuron is modulated by the stimulus signal nor do they modulate the choice signal and so the two neurons do not have II.
Supplemental Figure S3. Network structure of neurons with CI, but not II, neurons with greatest peak II magnitudes, and neurons with lowest II-peak latency but with more strict selection.
threshold. Related to Figure 4. **A.** Functional networks of short (S)- and long (L)-timescale interactions amongst neurons with high CI, but not II, were estimated using GC analysis for each behavioral choice. 20 exclusively CI neurons with above-threshold peak CI and sub-threshold peak II that had the shortest CI peak latency were selected for GC network analysis in each session with at least 20 CI neurons. Number of links, number of subnetworks, size of subnetworks, and statistical strength of links are represented as means ± 2 SEM. Asterisks indicate statistically significant differences based on Wilcoxon’s signed rank test (p<0.05). See also Supp. Table S3. **B.** Network statistics were used to train an SVM to classify into correct or incorrect decisions. Across timescale and selection of neurons—except CI S-timescales—decisions were predicted significantly better than chance (p<0.001). S-timescale network structure of CI neurons was decoded at chance-level accuracy, less than of low-latency II neurons (p<0.001), shown in Fig. 4. L-timescale network structure had higher decoding accuracy, and CI neuronal networks were decoded with similar accuracy (p=0.708). A two-sample t-test (p<0.05) was used to compare to neurons with low-latency II, and a one-sample t-test (p<0.05) to compare performance with chance decoding accuracy. **C.** Network statistics of greatest peak II magnitude neurons are shown in the same format as in panel A. Network statistics differed by timescale and behavioral choice similarly to network statistics of low II-peak latency neurons (Figure 4C). See also Supplemental Table S4. **D.** Network statistics were used to train an SVM to classify into correct or incorrect decisions. Across timescale and selection of neurons, decisions were predicted significantly better than chance (p<0.001). S-timescale network structure of high-magnitude II neurons was better decoded than of highly responsive neurons (p<0.001). L-timescale network structures had high decoding accuracy, but highly responsive neuronal networks were better decoded (p<0.001). **E.** Network statistics of low II-peak latency neurons chosen with II threshold of p<0.05 (see methods) are shown in the same format as in panel A. Network statistics differed by timescale and behavioral choice similarly to network statistics of low II-peak latency neurons (Figure 4C). Network structure of neurons with lowest II-peak latency is robust to selection
threshold. See also Supplemental Table S5. F. Network statistics were used to train an SVM to classify into correct or incorrect decisions. Across timescale and selection of neurons, decisions were predicted significantly better than chance (p<0.001). S-timescale network structure of low I1-peak latency neurons was better decoded than of highly responsive neurons (p<0.001). L-timescale network structures had high decoding accuracy, and low I1-peak latency neuronal networks were still better decoded (p<0.001). Thus, network structure of low I1-peak latency neurons is robust to choice of I1 threshold. Importantly, decoding accuracies are higher (83.3%) with the lower threshold than our main result in Fig. 4C, but distributions are more skewed. Asterisks indicate statistically significant differences. Wilcoxon’s signed rank test (p<0.05) was used in panels A, C, and E, a two-sample t-test (p<0.05) to compare to neurons with high activity, and a one-sample t-test (p<0.05) to compare performance with chance decoding accuracy in panels B, D, and F.
Supplemental Figure S4. The normalized time-lagged redundancy index showed that GC-linked pairs of neurons in L-timescale networks shared more redundant information (II, SI, CI) than GC-unlinked pairs of neurons (see Figure 6 in the main text for a comparison to S-timescale networks). Related to Figure 6. We report no difference in redundancy index between groups of positive and negative GC-linked neurons. Statistical comparisons between groups are made with a two-sample t-test (*p<0.05; **p<0.01; ***p<0.001).
Supplemental Figure S5. Stimulus information of significant II neurons and contribution of noise correlation to joint information of neural pairs during correct and incorrect behavior. Related to Figure 6. A. Stimulus information was computed separately for correct and incorrect trials for significant II neurons at the time peak of each neuron’s information. Stimulus information was higher in correct trials. The upper and lower edges of the boxes show the 75th and 25th percentiles, respectively, and the horizontal line marks the sample median. B. Using the information breakdown approach of (Pola et al., 2003), we broke down the contribution of noise correlations to the joint information carried by neuron pairs into the finer sub-components of stimulus-independent (left panel) and stimulus-dependent (right panel) noise correlations, separately for GC-linked and GC-unlinked pairs. Stimulus-dependent information decreased in incorrect trials for both groups of cells, while stimulus-dependent information increased in incorrect trials for GC-unlinked pairs. Bar plots show mean ± SEM. Results are reported in bits (as opposed to Fig. 6 of the main text where we plotted normalized redundancy/synergy values). To avoid systematic error (bias) in the estimation of information due to the different number of correct and error trials, we equalized the number of correct and incorrect trials by randomly subsampling the correct trials. Asterisks indicate statistically significant differences computed with a Wilcoxon’s signed rank test (*p<0.05, ***p<0.001). The synergy between neurons during incorrect trials shown in Fig. 6D, despite having positive signal and noise correlations, is due to
the major decrease of signal correlations, through the deterioration of the stimulus information (panel A), and the decrease of noise correlation strengths. Panel B suggests that the decrease of signal and noise correlation strengths greatly diminished the information-limiting effects of stimulus-independent correlations and left only the information enhancing effect of stimulus-dependent correlations, which led to synergy.
Supplemental Figure S6. Simulated example for assessing the use of the proposed parametrization of the integration window lengths in Granger causality (GC) network inference. Related to STAR Methods. A. Simulated responses of 10 neurons, shown averaged over 10 trials of 150 time samples in the left panel, were generated based on an underlying network of long (L) and short (S) timescale interactions (right subpanels). B. GC analysis using the short integration window identifies true S-timescale interactions, while expectedly discarding the L-timescale influences. False discovery rate (FDR) control prunes weak spurious interactions and retains significant links. C. Employing the L integration window for GC analysis captures both S and L influences, and after FDR control, the true functional connectivity is inferred correctly.
**SUPPLEMENTAL TABLES**

|        | # Links     |        | # Subnets     |        | Subnet Size     |        | Link Strength     |        |
|--------|-------------|--------|---------------|--------|-----------------|--------|------------------|--------|
| H      | S: 8.25 ± 1.61 | L: 8.33 ± 1.49 | p-value: 0.97 | S: 1.58 ± 0.19 | L: 2.08 ± 0.31 | p-value: 0.19 | S: 8.11 ± 0.75 | L: 4.16 ± 0.61 | p-value: 0.333 |
| M      | S: 2.08 ± 1.05 | L: 21.42 ± 6.10 | p-value: 0.009 | S: 0.63 ± 0.24 | L: 1.50 ± 0.26 | p-value: 0.074 | S: 3.30 ± 0.99 | L: 7.94 ± 1.91 | p-value: 0.041 |
| C      | S: 2.58 ± 0.91 | L: 4.58 ± 2.32 | p-value: 0.005 | S: 0.34 | L: 0.167 | p-value: 0.009 | S: 0.19 | L: 0.073 | p-value: 0.075 |
| F      | S: 2.33 ± 0.73 | L: 20.5 ± 3.90 | p-value: 0.632 | S: 0.002 | L: 0.33 | p-value: 0.33 | S: 0.298 | L: 0.357 | p-value: 0.009 |

Supplemental Table S1. Statistical comparisons of GC network structure across short (S) and long (L) timescales, and behavioral choice categories — hit (H), miss (M), correct-rejection (C), and false-alarm (F) — using Wilcoxon’s signed rank test (p<0.05). See also Fig. 4C.
Supplemental Table S2. Highly responsive neurons: statistical comparisons of GC network structure across short (S) and long (L) timescales, and behavioral choice categories — hit (H), miss (M), correct-rejection (C), and false-alarm (F) — using Wilcoxon’s signed rank test (p<0.05). See also Figure 4.

|        | # Links  | # Subnets | Subnet Size | Link Strength |
|--------|----------|-----------|-------------|---------------|
|        | S        | L         | p-value     | S             | L             | p-value     | S             | L             | p-value     |
| H      | 8.41 ± 1.60 | 13.91 ± 2.885 | 0.102 | 4.64 ± 0.556 | 4.48 ± 0.486 | 0.836 | 0.91 ± 0.009 | 0.88 ± 0.008 | 0.023 |
| M      | 1.88 ± 0.453 | 29.91 ± 4.544 | <0.001 | 11.01 ± 1.174 | 8.8 ± 0.708 | <0.001 | 0.92 ± 0.007 | 0.94 ± 0.009 | <0.001 |
| C      | 6.72 ± 1.112 | 12.31 ± 2.945 | 0.072 | 3.7 ± 0.396 | 4.68 ± 0.467 | 0.183 | 0.92 ± 0.007 | 0.90 ± 0.008 | 0.013 |
| F      | 6.63 ± 1.281 | 19.25 ± 3.057 | <0.001 | 1.88 ± 0.245 | 1.59 ± 0.148 | 0.33 | 0.90 ± 0.009 | 0.86 ± 0.009 | <0.001 |

p-value: <0.001, 0.001, 0.004, 0.007, 0.01, 0.01, 0.05, 0.001.
Supplemental Table S3. Neurons exclusively with CI: statistical comparisons of GC network structure across short (S) and long (L) timescales, and behavioral choice categories — hit (H), miss (M), correct-rejection (C), and false-alarm (F) — using Wilcoxon’s signed rank test (p<0.05).

See also Figure 4 and Supplemental Figure S3A.
Supplemental Table S4. Neurons with greatest II-peak magnitudes: statistical comparisons of GC network structure across short (S) and long (L) timescales, and behavioral choice categories — hit (H), miss (M), correct-rejection (C), and false-alarm (F) — using Wilcoxon’s signed rank test (p<0.05). See also Figure 4 and Supplemental Figure S3C.
### Supplemental Table S5

Neurons with low IL-peak latency (threshold p<0.05): statistical comparisons of GC network structure across short (S) and long (L) timescales, and behavioral choice categories — hit (H), miss (M), correct-rejection (C), and false-alarm (F) – using Wilcoxon’s signed rank test (p<0.05). See also Figure 4 and Supplemental Figure S3E.

|   | S     | L     | p-value | S     | L     | p-value | S     | L     | p-value | S     | L     | p-value |
|---|-------|-------|---------|-------|-------|---------|-------|-------|---------|-------|-------|---------|
| H | 12.9 ± 2.76 | 11.6 ± 3.02 | 0.919 | 1.86 ± 0.46 | 2.43 ± 0.30 | 0.32 | 5.62 ± 1.15 | 4.35 ± 0.96 | 0.409 | 0.90 ± 0.008 | 0.90 ± 0.010 | 0.801 |
| M | 1.00 ± 0.53 | 21.7 ± 5.78 | 0.012 | 0.71 ± 0.29 | 1.71 ± 0.29 | 0.029 | 2.40 ± 0.24 | 8.33 ± 2.02 | 0.014 | 0.89 ± 0.004 | 0.85 ± 0.008 | <0.001 |
| C | 5.14 ± 2.41 | 7.43 ± 2.53 | 0.526 | 1.71 ± 0.71 | 2.00 ± 0.38 | 0.732 | 3.08 ± 0.47 | 4.00 ± 0.78 | 0.327 | 0.91 ± 0.14 | 0.93 ± 0.019 | 0.654 |
| F | 2.00 ± 0.58 | 19.6 ± 8.72 | 0.099 | 1.57 ± 0.43 | 1.86 ± 0.26 | 0.562 | 2.27 ± 0.20 | 6.85 ± 1.74 | 0.022 | 0.95 ± 0.023 | 0.86 ± 0.019 | 0.019 |

# Links
# Subnets
Subnet Size
Link Strength

|   | S     | L     | p-value | S     | L     | p-value | S     | L     | p-value | S     | L     | p-value |
|---|-------|-------|---------|-------|-------|---------|-------|-------|---------|-------|-------|---------|
| H | 0.007 | 0.154 |         | 0.061 | 0.11  |         | 0.017 | 0.094 |         | 0.659 | 0.001 |         |
| M | 5.14 ± 2.41 | 7.43 ± 2.53 | 0.526 | 1.71 ± 0.71 | 2.00 ± 0.38 | 0.732 | 3.08 ± 0.47 | 4.00 ± 0.78 | 0.327 | 0.91 ± 0.14 | 0.93 ± 0.019 | 0.654 |
| C | 2.00 ± 0.58 | 19.6 ± 8.72 | 0.099 | 1.57 ± 0.43 | 1.86 ± 0.26 | 0.562 | 2.27 ± 0.20 | 6.85 ± 1.74 | 0.022 | 0.95 ± 0.023 | 0.86 ± 0.019 | 0.019 |
| F | 0.247 | 0.223 |         | 0.887 | 0.762 |         | 0.131 | 0.154 |         | 0.311 | 0.037 |         |
Supplemental Table S6. Supplemental statistical comparisons of correct/incorrect decision GC network structure by stimulus — i.e., hit (H) vs. correct-rejection (C), and miss (M) vs. false-alarm (F) — for short (S) and long (L) timescales using Wilcoxon’s signed rank test (p<0.05). Comparisons performed for networks of low II-peak latency neurons (see also Figure 4 and Table S1); highly responsive neurons (see also Supp. Table S2); CI neurons (see also Supp. Fig. S3A-B and Table S3); and high-magnitude II neurons (see also Supp. Fig. S3C-D and Supp. Table S4).