Supplementary Materials

Persistent neural activity in the human frontal cortex when maintaining space that is “off the map”

Kyeong-Jin Tark and Clayton E. Curtis

Supplementary Fig. 1. Group average performance on the auditory spatial working memory task as a function of the delay length. Importantly, accuracy did not change as a function of the delay lengths used.

Supplementary Fig. 2. Picture of the small microphone placed in a subject’s ear canal. Recordings of sounds around the subject’s head were used to build the sound files used in the fMRI experiment of auditory spatial working memory.
Supplementary Fig. 3. Cue sounds recorded from within the ear canals of an example subject show differences in the interaural level of sound intensity when comparing sounds originating from the left and right of the head. (a) Schematic of cued sound locations around the head. Plot of the intensity of the recorded sounds from the right ear minus the left ear for each position around the front (b) and back (d) of the subject’s head. (c) Plot of the average sound intensity across all frequencies for each location. Across all frequencies, the intensity level of the sound (dB) is greater in the ear closer to the sound source. These interaural differences in intensity levels can be used for sound localization, especially for left and right space.
**Supplementary Fig. 4.** Cue sounds recorded from within the ear canals of an example subject show differences in the interaural level of sound intensity when comparing sounds originating from the front and back of the head. (a) Schematic of cued sound locations around the head. Arrows indicate how the data was organized for the plots in (b) and (c). (b) Plot of the intensity of the recorded sounds from front minus back space for the ears combined. (c) Plot of the average sound intensity across all frequencies for each location moving from directly in front to directly behind the head. These differences in interaural intensity levels can be used for sound localization, even when discerning between front and back space.

**Supplementary Fig. 5.** Cue sounds recorded from within the ear canals of an example subject show differences in the interaural timing of sounds from around the head. (a) Schematic of cued sound locations around the head. (b) Plot of difference in sound onset times in right minus left ear canal recordings for each position around the head. The differences are minimal directly in front and back of head and maximal at the sides. These differences in interaural timing can be used for sound localization, especially for right and left space.
Delay specificity - Because the hemodynamic response (HR) acts as a low-pass filter on neural activity, neural activity from trial events that are adjacent in time is difficult to separate. In the current study we attempt to separate cue evoked transient activity from sustained delay activity. Our approach took two forms. First, the GLM separately modeled cue activity with a HR impulse function and delay period activity with a linearly increasing ramp function. This ramp helped bias the model towards the latter portions of the delay, in essence, weighting the delay estimate by its distance from the cue epoch. Second, in our time course analyses, we averaged the signal separately for the peak of the cue response (2 – 6 s following cue onset) and across the variable delay (6 s - end of delay period, up to 14 s) in the superior precentral sulcus (sPCS). Here, we report supplementary analyses on the sPCS time-courses only using the last part of the delay, 10 – 14 s after the cue onset. In summary, restricting our analyses to the end of the delay does not change any of the results from the analysis of the full delay period. BOLD signal in sPCS was significantly above baseline during the last 10 – 14 s of the delay for both front ($t_{[12]} = 4.40, P < 0.001$) and back ($t_{[12]} = 3.58, P < 0.002$) trials. Moreover, the delay period activity in the sPCS during the last 10 – 14s did not differ between front and back trials ($t_{[12]} = 0.19, P < 0.85$). Finally, the sPCS BOLD activity during the last 10-14s of the delay period showed a contralateral greater than ipsilateral effect for both front ($t_{[12]} = 2.27, P = 0.03$) and back ($t_{[12]} = 2.57, P < 0.02$) trials.

Multi-voxel pattern analysis (MVPA) – We tested the hypothesis that we could predict whether subjects are maintaining front or back space using the multivoxel patterns of delay period BOLD activity using MVPA (http://www.csbmb.princeton.edu/mvpa/). First, we used 320 gray matter voxels along the bilateral sPCS. The BOLD epochs used for analysis were shifted by 4 seconds to adjust for the hemodynamic lag. For each trial, we averaged the BOLD signal throughout the delay period. We trained a classifier using all but 4 trials (i.e. 2 trials left out per condition), and tested to see if the classifier could use the delay period activity of the 4 trials to predict whether it was a front or back space trial. We repeated this procedure 300 times, randomly leaving out 4 different trials each iteration to create average classification accuracies for each subject.

Supplementary Fig. 6. Results from MVPA. The multivoxel pattern of delay period BOLD data from the sPCS cannot be used to reliably differentiate between the maintenance of memoranda in front of or in back of a subject’s head.
The classifier performance of all subjects is shown in Supplementary Figure 5. Chance is 50%, and based on randomization tests, significance is approximately 62.5%. The accuracy of the most subjects remained around chance, indicating that the sPCS delay period activity could not be used to predict whether the memoranda was in front or behind the head. Therefore, in agreement with the results from the standard univariate analyses in the main paper, we do not find differences in the sPCS activity for front and back trials. Obviously it is difficult to interpret null effects and we are certainly not suggesting that these results indicate that the neurons in the FEF are insensitive to differential representations of front and back space. Our data do, however, show that the activity in the putative FEF does persist above baseline during the maintenance of locations to which a saccade cannot be programmed. In the present experiment, BOLD data cannot differentiate between front and back trials. One key assumption that multivoxel pattern analyses make is that the concentration and/or distribution of two cell types must be segregated across the voxels of interest. Consider that the FEF may contain both eye and head centered neurons that would be differentially sensitive to maintenance of front and back space. MVPA assumes that putative eye and head-centered neurons must be spatially segregated in the FEF cortex. At the very least, the voxels in the sPCS must contain different proportions of eye and head-centered neurons. Additionally, the resolution of our imaging must be fine enough to detect the differential distributions if they exist. The validity of these assumptions is unknown and therefore prevents us from drawing firm conclusions from the MVPA.

**Supplementary Tables.** Peak Montreal Neurological Institute (MNI) volumetric coordinates for active foci.

**Supplementary Table 1.** Group averaged delay period activity in sPCS during auditory spatial working memory vs. saccade localizer task (Fig. 6a).

| Hemi | ASWM Delay (“A”) | Saccade (“S”) |
|------|------------------|---------------|
|      | x                | y             | z    | x    | y    | z    |
| L    | -28.5            | -12.7         | 50.6 | -29.5| -4.3 | 46.6 |
| R    | 47.0             | -5.7          | 49.5 | 40.7 | -6.9 | 56.7 |

**Supplementary Table 2.** Group averaged delay period activity in sPCS during auditory spatial working memory vs. visual spatial working memory (Fig. 6b)

| Hemi | Auditory Front (“F”) | Auditory Back (“B”) | Visual (“V_1”, “V_2”) |
|------|----------------------|---------------------|-----------------------|
|      | x                    | y                   | z                    | x    | y    | z    | x    | y    | z    |
| L    | -28.2                | -5.4                | 60.3                 | -31.2| -12.7| 58.0 | -26.2| -9.9 | 52.2 |
|      |                      |                     |                      | -39.9| -8.2 | 61.4 |
| R    | 47.0                 | -7.0                | 53.4                 | 45.0 | -6.0 | 51.1 | 41.1 | -10.5| 64.3 |
**Supplementary References**

1. Haxby, J.V., *et al.* Distributed and overlapping representations of faces and objects in ventral temporal cortex. *Science* **293**, 2425-2430 (2001).
2. Kamitani, Y. & Tong, F. Decoding the visual and subjective contents of the human brain. *Nat Neurosci* **8**, 679-685 (2005).
3. Norman, K.A., Polyn, S.M., Detre, G.J. & Haxby, J.V. Beyond mind-reading: multi-voxel pattern analysis of fMRI data. *Trends Cogn Sci* **10**, 424-430 (2006).