Overlapping Neuronal Population Responses in the Human Parietal Cortex during Visuospatial Attention and Arithmetic Processing

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Abstract

■ Engagement of posterior parietal cortex (PPC) in visuospatial attention and arithmetic processing has been extensively documented using neuroimaging methods. Numerous studies have suggested a close connection between visuospatial attention and arithmetic processing. However, the extant evidence in humans stems from neuroimaging methods that have relied on group analyses without much knowledge about the profile of neurophysiological engagement within localized neuronal populations at the individual brain level. Hence, it has remained unclear if the overlap of two functions in the PPC is the product of averaging, or they truly stem from a common profile of activity within the same neuronal populations in the human PPC. In the current study, we leveraged the anatomical precision and high signal-to-noise ratio of intracranial electrocorticography and probed the engagement of discrete PPC neuronal populations in seven neurosurgical patients ($n =$ 179 total PPC sites covered; 26 sites on average per individual participant). We aimed to study the extent of parietal activations within each individual brain during visuospatial attention versus arithmetic tasks and the profile of electrophysiological responses within a given recording site during these tasks. Our findings indicated that about 40% of PPC sites did not respond to either visuospatial attention or arithmetic stimuli—or episodic memory conditions that were used as an adjunct control condition. Of those that were activated during either visuospatial attention or arithmetic conditions, a large majority showed overlapping responses during both visuospatial attention and arithmetic conditions. Most interestingly, responses during arithmetic processing were greatest in sites along the intraparietal sulcus region showing preference to contralateral, instead of ipsilateral, visual probes in the visuospatial attention task. Our results provide novel data about the relationship between numerical and spatial orientation at the neuronal population level and shed light on the complex functional organization of the PPC that could not be attained with noninvasive methods. ■

INTRODUCTION

The posterior parietal cortex (PPC) is known to be important for various cognitive functions such as visuospatial attention (Corbetta, Kincade, & Shulman, 2002). Numerous studies have suggested a close connection between visuospatial attention and arithmetic processing in the PPC, but the precise neuronal evidence for such an interaction has been missing (Eger, Pinel, Dehaene, & Kleinschmidt, 2015; Roitman, Brannon, & Platt, 2012; Nieder, Diester, & Tudusciuc, 2006; Cohen Kadosh et al., 2005; Dehaene, Spelke, Pinel, Stanescu, & Tsivkin, 1999).

Majority of current evidence about the human PPC stems from neuroimaging studies that have limited temporal and anatomical resolution. The low signal-to-noise ratio of imaging methods often leads to group-based averaging of the recorded signals, and as a result, a large mantle of the PPC is often shown to be activated in any of these functions (Culham & Kanwisher, 2001) and the anatomical source of the activations at the neuronal population level within the human brain remains unknown. As a result, several questions have remained largely open: first, how much of the individual participant's PPC mantle is usually engaged in any of these functions. Are there areas as large as the group-based BOLD maps suggest? Second, are there any populations of neurons that show preferential or entirely selective activations during visuospatial attention and arithmetic processing? Third, can the profile of activity of a PPC site during visuospatial attention predict its response during arithmetic processing?

Evidence from electrophysiological studies in nonhuman primates (Nieder, 2004) and few studies in humans (Daitch et al., 2016) have demonstrated a remarkable functional selectivity within specific parietal neuronal ensembles for arithmetic processing. For example, neurons with selective tuning to a preferred numerosity have

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been described in the primate homologue to human intraparietal sulcus (IPS) region (i.e., the ventral intraparietal area and the lateral intraparietal area). However, the same region is also known to receive bottom–up signals to process visuospatial information for shifting attention and planning eye movements (Viswanathan & Nieder, 2013; Buschman & Miller, 2007; Nieder, 2004; Andersen & Buneo, 2002). This raises the question of whether there might be neuronal populations with overlapping functions for both visuospatial attention and numerical processing.

The aim of our current study was to leverage the high signal-to-noise ratio and anatomical precision of electrocorticography (ECoG) recordings from distinct neural populations within the individual human brains (Parvizi & Kastner, 2018) to address the remaining open questions listed above. We first aimed to study the scope of parietal activations during visuospatial attention and arithmetic tasks (Aim 1). Next, by comparing the functional responses in different tasks within a given recording site, we explored if there were groups of neuronal populations with distinct and/or overlapping responses (Aim 2).

We are mindful that our study is based on observations in a small number of participants, but we like to remind the reader that epilepsy does not affect the parietal lobe as frequently as the temporal lobes and parietal lobes are very rarely implanted with electrodes for evaluation of epilepsy surgery (Engel, 1996). It is even more difficult to find participants who are implanted in the PPC region and participate across a combination of several experiments of interest. As such, our unique cohort of participant patients provided unique information that cannot be attained with noninvasive methods.

METHODS

Participants and Recording

Our data were acquired in the last 12 years at our center. Patients were implanted with subdural and depth intracranial electrodes in the PPC and adjacent areas. This procedure was performed as part of a clinical presurgical evaluation at Stanford University Medical Center. Each patient was monitored in the hospital for ~6–10 days after surgery. Electrode locations were determined by clinical needs. Demographic information for each participant is included in Table 1. All participants had provided written informed consent to participate in all the experiments, which were approved by the Stanford University institutional review board. ECoG data were obtained at ≥1000 Hz (Participant 1 [S1] = 1017.25 Hz, S2 = 1000 Hz, S3 = 3051.76 Hz, S4 = 3051.76 Hz, S5 = 3051.76 Hz, S6 = 1000 Hz, S7 = 1000 Hz) through a 128-channel recording system (Tucker Davis Technologies; www.tdt .com). For subdural grids and strips, electrode size was commonly 2.3 mm in diameter with a center-to-center interelectrode spacing of 10 mm, or 5 mm for higher-density arrays. For depth electrodes, contact size was 0.86 mm in diameter and 2.29 mm in height with interelectrode spacing of 5–10 mm. We selected the recording sites that fell within the PPC based on participant-specific anatomical space (see anatomical boundary of each subregion in the parietal cortex in Figure 1B). In total, we considered information from 179 recording sites within the LPC with 92 sites in the superior parietal lobule (SPL), 25 sites in the supramarginal gyrus (SMG), 42 sites in the angular gyrus (AG), 20 sites in the IPS (see electrode coverage within each subregion in Figure 1B).

Anatomic Localizations of Electrodes

Imaging data were acquired at Stanford University and then segmented to distinguish gray and white matter using FreeSurfer (Fischl, 2012; surfer.nmr.mgh.harvard .edu). Postimplant CT scans were coregistered to the preoperative MRI anatomical brain volume. For each participant, electrodes were localized in BioImage Suite (Papademetris et al., 2006; bioimagesuiteweb.github.io /webapp) and displayed on the participants' own reconstructed 3-D cortical surface using the iELVis MATLAB toolbox (Groppe et al., 2017). Finally, to ensure maximum precision and unbiased classification, all electrodes

Table 1. Participant Information

Participants	Gender	Handedness	Coverage	Implant	No. of Electrodes	Brain Areas	Spatial Task	Arithmetic Task
S1	M	Right	RH	ECoG	35 (112)	P, O, T	1A	2A
S2	F	Right	RH	ECoG	27 (158)	P, T	1B	2B
S3	F	Right	RH	ECoG	20 (64)	P, O	1C	2A
S4	M	Right	RH	ECoG	20 (118)	P, O	1C	2A
S5	F	Right	LH	ECoG	32 (106)	F, P, O	1A	2A
S6	M	Right	Both	sEEG	27 (166)	F, P, T	1B	2A
S7	M	Right	Both	sEEG	18 (152)	F, P, T	1B	2B

Coverage by lobe: P, parietal; O, occipital; T, temporal; RH, right hemisphere. The number of electrodes indicates those that were localized in the PPC relative to all implanted electrodes (in parentheses). M = male; F = female.
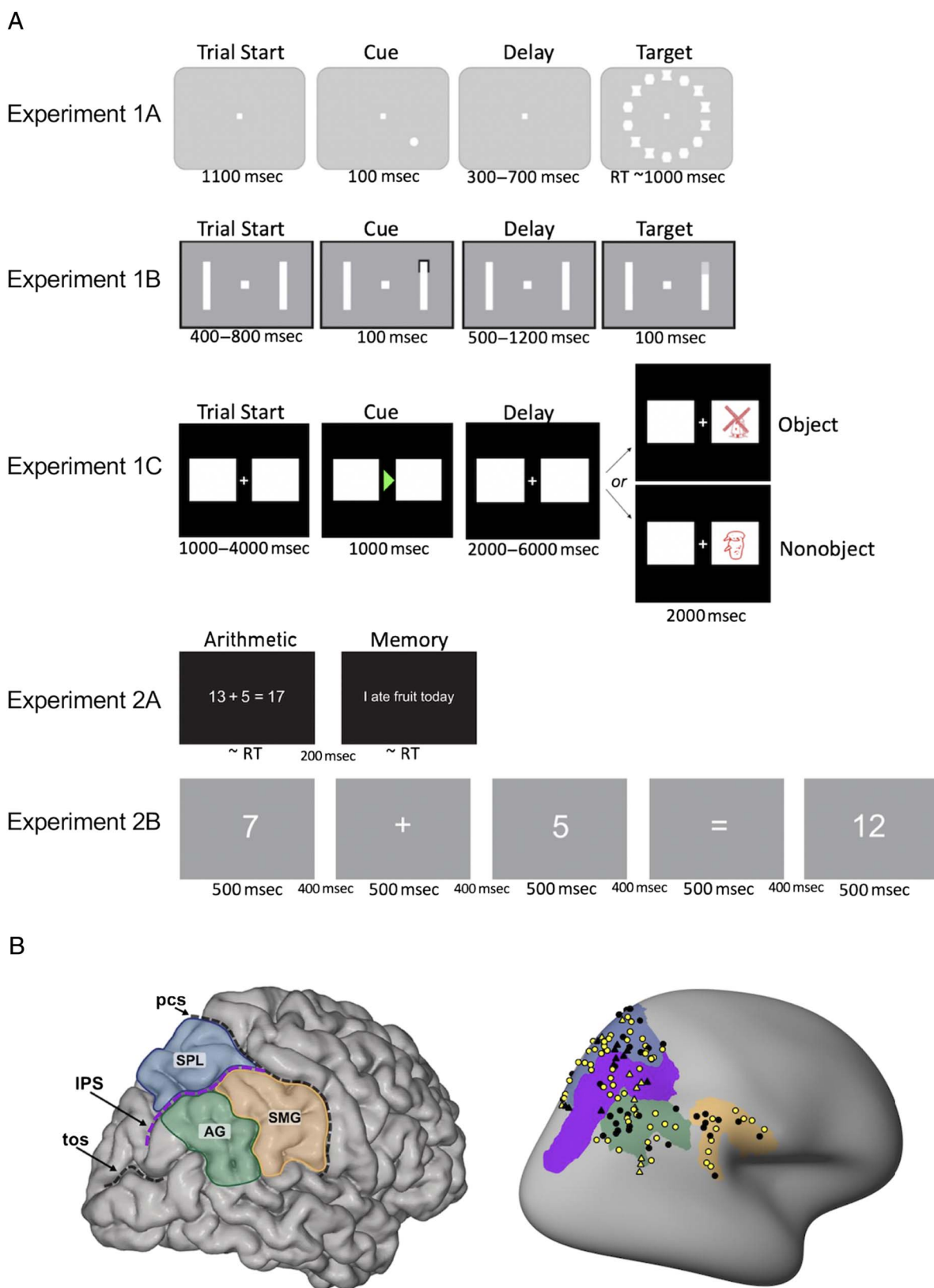
Figure 1. Tasks, anatomical subdivisions, and electrode coverage. (A) Illustration of the tasks. See Cognitive Experiments for a detailed description of each task. (B) Anatomical subdivisions (left) and electrode coverage within the PPC from a slightly posterior viewpoint. The PPC sites are projected onto a single right hemisphere in Montreal Neurological Institute space (see Anatomic Localizations of Electrodes in the Methods section). Dots represent subdual electrodes, and triangles represent depth electrodes with the yellow ones indicating task-active sites and the black ones indicating nonactive sites in the task conditions (relative to baseline). pcs = postcentral sulcus; tos = transverse occipital sulcus.

were labeled manually by a senior neuroanatomist blind to the results and based on the subdivision of the PPC shown in Figure 1B. For group-level analysis, each individual brain surface was warped to match with FreeSurfer Average brain atlas (fsaverage brain), which was a surface-based transformation into fsaverage coordinate system (Fischl, Sereno, Tootell, & Dale, 1999). This transformation assigns each point of the patient's spherical surface to the nearest neighbor on the fsaverage brain spherical surface, which results in one-to-one vertex correspondence. Next, we snapped each electrode to the closest native brain vertex and calculated the fsaverage brain coordinate of them.

Experimental Tasks

In the last 12 years, we found only seven participants with relevant coverage in the PPL who had also participated in visuospatial attention, arithmetic, and memory tasks. We are mindful that the tasks administered in every participant were not entirely identical, but we made sure to include in our analyses only the parameters that were common across the tasks.

Each task was conducted at the patient's bedside using Psychophysics Toolbox (psychtoolbox.org/) running on the Apple Macintosh OSX operating system. The computer screen was placed at a distance of ~70 cm from participants' eyes. We obtained ECoG data during visuospatial attention, arithmetic, and memory tasks (Figure 1A). Each participant performed one version of visuospatial attention tasks (Experiments 1A, 1B, and 1C) and one version of arithmetic and memory tasks (Experiments 2A and 2B) separately (see experiment version for each participant in Table 1). Experiments 1A, 1B, and 1C are classical variants of visuospatial attention tasks that have been adapted in recent studies (Helfrich et al., 2018). Experiments 2A and 2B are known from our past studies to reliably assess functional selectivity of neuron populations within the LPC during arithmetic processing (Daitch et al., 2016).

Experiment 1A: Flanker Task (Visuospatial Attention)

Participants 1 and 5 performed a variant of the Eriksen flanker task, which was adopted in a recent ECoG study (Martin et al., 2019). Each trial started with a central fixation point, and the participant was instructed to maintain fixation throughout the duration of each trial. After 1100 msec, a circular spatial cue was presented for 100 msec at a pseudorandomly chosen peripheral location, followed by a variable delay period (300–700 msec). Then, a circular array of equally spaced barrel and bowtie shapes was displayed for 2000 msec or until the participants responded. Participants had to judge whether a barrel or bowtie shape was presented at the cued location by pressing a left or right button, respectively.

Experiment 1B: Egly–Driver Task (Visuospatial Attention)

Participants 2, 6, and 7 performed a variant of the Egly–Driver task (Egly, Driver, & Rafal, 1994). Each trial started with a central fixation that was presented for 400–800 msec. Then, two vertical or horizontal bars appeared, followed by a variable delay period (400–800 msec). A spatial cue was presented around one bar in the periphery (100 msec) indicating the most likely location where the target would appear. The cue was equally likely to be presented at any of the four quadrants. After a variable delay (500–1200 msec), the target was presented (in 90% trials) either at the cued location or at an uncued location that was either on the same bar or on the other bar. Participants were asked to detect the target by pressing the space button.

Experiment 1C: Posner Task (Visuospatial Attention)

Participants 3 and 4 performed a variant of Posner cueing task (Posner, Snyder, & Davidson, 1980). In this task, participants were presented with a fixation in the middle of the screen and a white box on each side. Participants had to keep eyes on the fixation throughout the whole task. After a random delay period, a green triangle arrow was presented at the fixation position for 1000 msec, pointing to either the left or right box where a drawing was most likely to appear. Then, a drawing was presented in the left or right box (in 75% trials) after a certain period (2–6 sec). Participants were instructed to decide whether the drawing was a real object (like a windmill, for example) or a nonsense drawing by pressing the buttons on the keyboard.

Experiment 2A: Simultaneously Presented Arithmetic Calculations and Autobiographical Memory

Participants 1, 3, 4, 5, and 6 were instructed to make true/false judgments about a series of autobiographical memory statements (e.g., "I ate fruit yesterday"). Participants had to respond as fast and accurately as possible, by pressing one of the response buttons. These statements were interspersed with arithmetic calculations (e.g., "13 + 5 = 18") or fixation periods (5 or 10 sec) during which participants were asked to fixate on a center crosshair. A 200-msec intertrial interval separated trials.

Experiment 2B: Sequentially Presented Arithmetic Calculations and Autobiographical Memory

Participants 2 and 7 were asked to make true/false judgments about a series of arithmetic statements. These statements were presented one number/symbol/word at a time (e.g., "1" "+" "3" "=" "4"; "I" "ate" "fruit" "yesterday"). Each number/symbol/word was presented for 500 msec with an ISI of 1 sec.

Disclaimer

Although the tasks performed by every participant were not entirely identical, we made sure to include in our analyses only the parameters that were common across the tasks. For the visuospatial attention tasks, we only focused on the cue period and used a crucial marker to estimate the effect of spatial attention, which is shown to exist among diverse spatial attention paradigms. For arithmetic calculation and autobiographical memory tasks, we chose a time window during which participants both read the stimulus and began to perform the computation and/or recall a memory in the two experimental tasks.

Preprocessing

Data preprocessing was completed using MATLAB (www.arithmeticworks.com) and iEEG preprocessing pipelines (github.com/LBCN-Stanford/lbcn_preproc). We used a recently validated method to detect epileptic activity in each recording site (Liu & Parvizi, 2019) and exclude it from further analysis. The signals were notch filtered at 60 Hz to remove electric interference and rereferenced to the mean of the filtered signals of all the nonexcluded electrodes. The rereferenced signal at each site was then band-pass filtered between 70 and 180 Hz (high-frequency broadband, HFB) using two-way, zero-lag, finite impulse response filters. The instantaneous amplitude of each band-limited signal was computed by taking the modulus of the Hilbert transformed signal. We subdivided the 70- to 180-Hz band (HFB) into bandpass windows with a width of 10 Hz and normalized the amplitude of each 10-Hz band signal by its own mean, and then these normalized amplitude time series were averaged together, yielding a single amplitude time course for the HFB band. Each event was epoched on the time window of −200 to 2000–5000 msec around the stimulus onset and then performed a baseline correction using a time window of 200 msec before the stimulus onset.

Functional Specialization

Epoched trials were averaged for each condition to obtain the mean HFB activity in each task. HFB signal is shown to be a reliable indicator for engagement of a given cortical site during a cognitive function (Parvizi & Kastner, 2018). Within the PPC, we identified two classes of sites: (1) "active sites," that is, those showing generic higher activity after the stimulus onset as compared to baseline during all tasks, and (2) "selective sites," that is, those showing selective to a particular condition in one or more tasks (e.g., spatial orientation, arithmetic and memory). To define selectivity, we analyzed each task separately and contrasted each given condition against the baseline peristimulus period as well as against the other conditions. For the visuospatial attention tasks, the conditions were left and right hemifield presentations of the cue. For the

visuospatial attention task, we classified the sites as (1) "space active," that is, if the site showed significantly higher HFB activity after the cue presentation versus baseline, and (2) "space selective (space orienting)," that is if the site showed (a) a significantly higher HFB activity after the cue onset versus baseline or (b) a significantly greater HFB response during cuing to contralateral versus ipsilateral hemifield. The latter criterion is a crucial marker to estimate the effect of spatial attention that can be seen by greater neural activity when attention is directed to the contralateral than ipsilateral side of the visual field (Yantis et al., 2002). For the arithmetic calculation task, the conditions were labeled as "arithmetic" and "memory." Specifically, sites were arithmetic active when they displayed a significantly higher HFB activity in the arithmetic condition versus baseline. Sites were arithmetic selective when they exhibited (1) a significantly greater HFB response during the arithmetic condition compared with baseline or (2) a significantly greater HFB response during the arithmetic condition (Raccah, Daitch, Kucyi, & Parvizi, 2018; Daitch et al., 2016). Sites were memory active when they showed significantly higher HFB activity during memory condition than baseline, whereas sites were memory selective when they displayed (1) a significantly greater HFB response during the memory condition compared with baseline or (2) a significantly higher HFB response during the memory than arithmetic condition. Finally, sites were nonactive when they showed a nonsignificant difference of HFB activity between tasks and baseline.

Statistical Analysis

To evaluate the significance of category-specific HFB responses, we first averaged the HFB power within a poststimulus window for each task condition and a time window of 200 msec before stimulus onset for baseline. For Experiment 1, we consider a time window of 200–400 msec after the cue onset. This time window was chosen because a late-onset activity (225 ± 11 msec) in the parietal cortex during spatial attention was predicted (Martin et al., 2019), which would also exclude early non-selective activity to the visual stimulus. For Experiment 2A, a time window of 0–1000 msec poststimulus was chosen during which participants read the presented stimulus and began to perform the computation or recall a memory. For Experiment 2B, we used a shorter time window of 100–400 msec after the last stimulus. These time window parameters were adapted in a previous study of our group, which has found the selective functional engagement of the LPC during numerical processing (Daitch et al., 2016). We then run paired permutation tests (5000 repetitions) to test for a difference in HFB power between a task condition and the baseline as well as unpaired permutation tests for different responses in HFB power between different task conditions ($p < .05$, false discovery rate [FDR] corrected for the number of sites tested within an individual participant). We used

cluster-based permutation tests (5000 repetitions) to figure out the time window during which there is a significant difference of HFB response between different task conditions ($p < .05$). To determine whether there is a statistically significant difference between the frequencies of sites in different categories, we performed χ^2 test with correction on the frequencies of sites showing category-specific responses.

RESULTS

We found seven patients in the course of 12 years of our practice who were implanted with intracranial electrodes in the PPC for clinical purposes and participated in cognitive tests. Demographic information for each participant is included in Table 1, and all patients' electrode coverage is displayed in Figure 1B.

Behavioral Results

Participants performed the tasks with greater than 80% accuracy on average. The accuracy and RT of each participant in the tasks and the variation are shown in Table 2. See also task paradigm in the Methods section and Figure 1A.

Task-dependent Activations in the PPC Recording Sites

In total, 179 recording sites were located within the PPC based on each patient's anatomical space (Figure 1B). Within all the PPC sites, 13 were excluded from further analysis because of the presence of artifacts. Using nonparametric permutation tests evaluating significant task-evoked changes in HFB activity during each task condition compared to baseline and using an FDR-corrected p value of <.05, we identified 98 "task-active sites" (i.e., significant activations during at least one task condition) within the PPC (Figure 1B). This suggests that, of all recording sites across the PPC, about 41% of the sites showed no significant engagement during visuospatial attention, numerical, or episodic memory conditions probed in our experiments.

Category-specific Responses in the PPC Sites

Within the active sites, we then identified six types of neural population responses during the tasks, which reflected the involvement of the PPC in the three cognitive (i.e., visuospatial attention, arithmetic, and autobiographical memory) domains. Patterns of activations are summarized in Figure 2A.

In the visuospatial attention condition, 74 sites responded significantly to the presentation of cue (relative to baseline). Of these, 30 showed higher HFB activity to cues presented in the contralateral compared to the ipsilateral visual field (Figure 2). We refer to these sites as "space-orienting" sites. Within these space-orienting sites, 14 sites were located in the SPL whereas three sites were located in the AG, 12 sites were in the IPS, and one site was located in the SMG. Only one site in the IPS showed the opposite spatial orienting effect with greater HFB response to cues presented in the ipsilateral than contralateral visual field.

In the arithmetic condition, we found 59 "arithmetic-active" sites within the PPC, that is, sites that had greater HFB activity during the arithmetic condition relative to baseline ($p < .05$ and FDR corrected; Figure 2A). Within the "arithmetic-active" sites, several sites, mostly in the SPL and along the IPS, had significantly greater HFB responses during the arithmetic condition relative to both memory and baseline conditions (24 of 166 PPC sites [14%]; $p < .05$, FDR corrected; Figure 2B and C). We refer to these active sites as "arithmetic selective," which is in line with our previous report of subregions in the PPC engaging selectively in arithmetic (Pinheiro-Chagas, Daitch, Parvizi, & Dehaene, 2018; Daitch et al., 2016). In Figure 2B, we show that only three of these sites from all recorded sites

Table 2. Behavioral Performance

	Spatial Attention Task		Arithmetic and Memory Task		
	Accuracy (%)	RT (SD; sec)	Arithmetic Accuracy (%)	Arithmetic RT (SD; sec)	Memory RT (SD; sec)
S1	91.07	0.40 (0.07)	85.42	2.85 (1.87)	2.59 (1.46)
S2	69.33	0.38 (0.24)	66.67	1.68 (0.93)	1.91 (0.75)
S3	90.18	0.27 (0.18)	83.33	3.57 (1.75)	2.29 (0.92)
S4	92.34	0.31 (0.11)	95.83	3.13 (1.41)	2.42 (1.16)
S5	82.83	0.92 (0.25)	90.00	5.78 (2.11)	3.10 (0.89)
S6	58.50	0.43 (0.09)	97.50	1.85 (0.60)	1.83 (0.97)
S7	78.22	0.55 (0.04)	69.44	1.99 (1.31)	2.40 (0.73)

This table shows the accuracy and average RT in the spatial attention, arithmetic, and memory tasks.
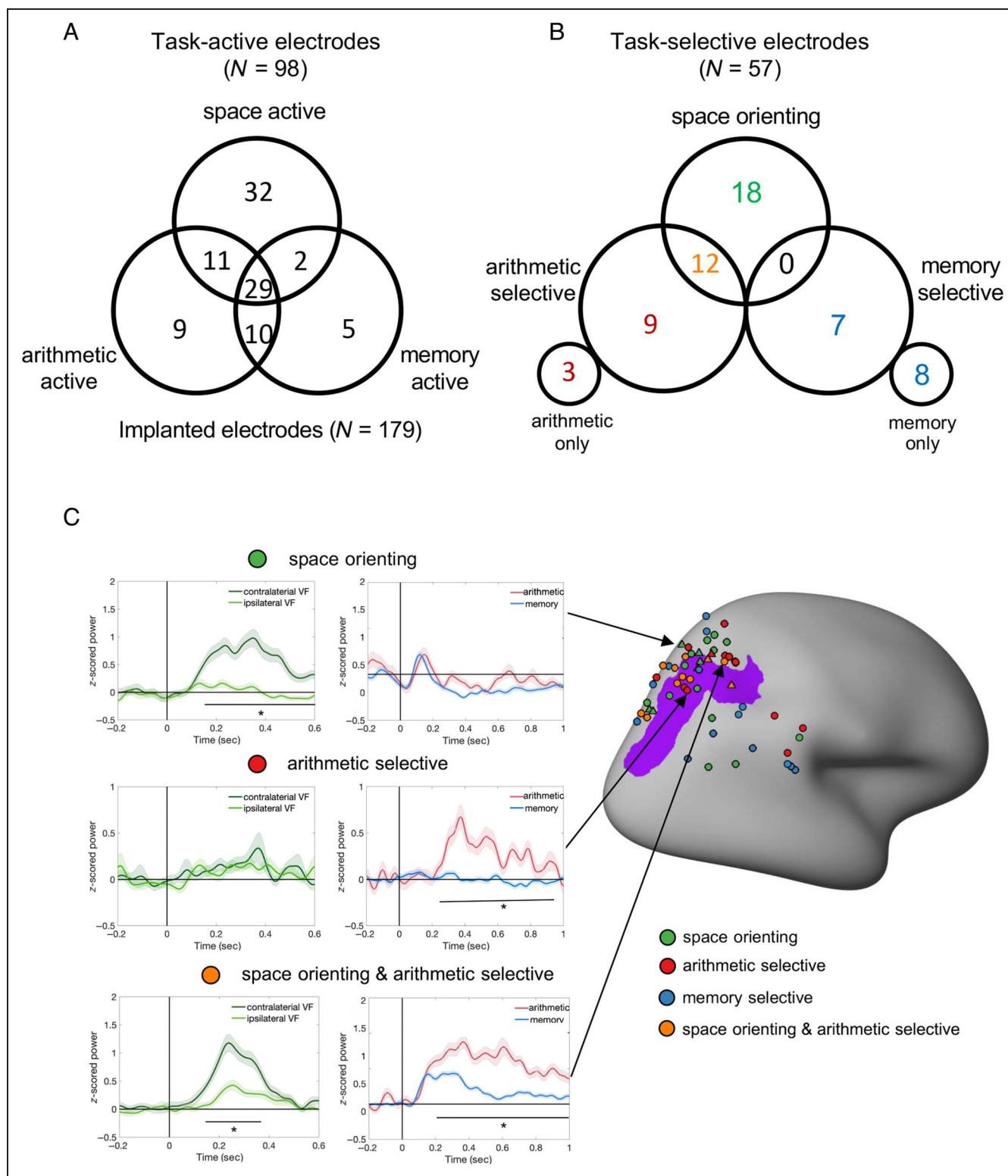
Figure 2. Spatiotemporal distribution of visuospatial orientation, arithmetic, and memory responses in the PPC. (A) Number of sites showing activation in the tasks compared with baseline within the PPC. (B) Number of sites that responded selectively to the visuospatial orientation, arithmetic, and memory conditions within the PPC. Small circles displayed the numbers of most "selective" sites, which showed selective responses to the arithmetic or memory condition and no response to visuospatial attention. Number colors represent specific functional response types shown in C. (C) Exemplar selective sites within the PPC that were space orienting and arithmetic selective only respectively, and sites that engaged in both visuospatial orientation and arithmetic processing. The time course shows the HFB activity averaged across trials. The shaded area denotes *SEM* across trials for each condition. Dots represent subdural electrodes and triangles represent depth electrodes. VF = visual field.

showed selective responses to the arithmetic condition compared to baseline and memory and showed no response to visuospatial attention.

In the memory condition, we found 46 "memory-active" sites that showed higher HFB activity in the memory condition than baseline ($p < .05$, FDR corrected). These sites were located in the SPL (24), AG (9), and SMG (13). In line with extant neuroimaging evidence (Rugg & King, 2018), six sites in the SMG, seven sites in the SPL, and two sites in the AG were more active during autobiographical memory than during arithmetic processing (15 of the PPC sites [9%]; $p < .05$, FDR corrected).

Distinct and Overlapping Activations during Task Conditions within the Human PPC

To address Aim 2 of the study, we compared the functional responses within a given recording site in each individual brain during the three cognitive conditions to explore their distinct and/or overlapping profile of activation. As summarized in Figure 2B and Table 3, within the "space-active" sites, we found 40 sites (54%) were also arithmetic active whereas 31 sites (42%) were memory active. There was no significant difference between the frequencies of sites in those two categories ($\chi^2 = 1.73, p = .19$). In other words, if a site was activated during the visuospatial attention condition, it was equally likely that the site also was active during the arithmetic or memory condition. However, space-active sites were statistically more likely to show arithmetic-selective (21 sites) than memory-selective (seven sites) responses ($\chi^2 = 7.44, p = .006$). Arithmetic preference in space-active sites was more noticeable in the subset of regions that showed preference to the contralateral visual fields (i.e., space-orienting sites). In addition to the space-active sites, we also found 24 "space-inactive" sites within which 19 sites were arithmetic active whereas five sites were arithmetic inactive. To assess if the overlap between spatial attention and arithmetic is because of chance, we performed χ^2 test on the frequencies of the overlapping electrodes in visuospatial attention and arithmetic. The result showed that the activations of the sites in these two functions were significantly related ($\chi^2 = 4.77, p = .03$ without correction; $\chi^2 = 3.78, p = .05$

with Yates's correction). Among the 30 space-orienting sites, there were 14 sites (47% of the "space-orienting" sites; Table 3) that were arithmetic active, whereas nine sites (30%) were memory active. Furthermore, 12 of the 30 space-orienting sites were also arithmetic selective ($p < .05$, FDR corrected), whereas none of the space-orienting sites were memory selective. We performed χ^2 test with correction to compare the frequencies of space-orienting sites that were also arithmetic selective and memory selective, respectively. The result showed that there were significantly more arithmetic-selective than memory-selective sites within the space-orienting sites in the PPC ($\chi^2 = 12.60, p = .004$), which indicated that among the space-orienting sites, there was a much higher probability of being arithmetic selective than memory selective. The degree of arithmetic selectivity (i.e., HFB power during the arithmetic vs. memory condition) was not different in space-orienting and space-active recording sites ($t = 0.82, p = .43$).

Within the 24 "arithmetic-selective" sites (including three arithmetic only, nine arithmetic selective but not spatial selective, and 12 arithmetic selective and spatial orienting), nine sites were located in the SPL (largely around the IPS) and three sites were located in the SMG (Figure 2B and C). We performed χ^2 test with correction to compare the frequencies of these arithmetic-selective but not spatial-selective sites that were localized in the SPL and SMG, respectively. There was no significant difference between the frequencies of sites in those two categories ($\chi^2 = 2.42, p = .12$). Across all participants and all electrodes, we found only three sites around the IPS and edging the SPL that had arithmetic-only responses (i.e., arithmetic selectivity compared to memory condition and no significant activation during visuospatial attention tasks; Figure 2B and C). Within the 15 "memory-selective" sites, eight of them were only selective in autobiographical memory and did not show activation during visuospatial attention (or arithmetic) conditions (Figure 2B and C).

Finally, a clear anatomical trend was noted for sites with overlapping arithmetic and space activations. These were mostly located along the anterior IPS and in SPL (Figure 2C). Those responding selectively during

Table 3. Summary of Sites Showing Category-specific Responses

N = 179	Arithmetic Active (n = 59)	Memory Active (n = 46)	Arithmetic Selective (n = 24)	Memory Selective (n = 15)
Space active (n = 74)	40 (54%)	31 (42%)	21 (28%)	7 (9%)
Space orienting (n = 30)	14 (47%)	9 (30%)	12 (40%)	0 (0)
χ^2 test on space-active sites	$\chi^2 = 1.73, p = .19$		$\chi^2 = 7.44, p = .006$	
χ^2 test on space-orienting sites	$\chi^2 = 1.13, p = .29$		$\chi^2 = 12.60, p = .004$	

This table displays the number and percentage of sites in each category in the visuospatial attention tasks (in the row) showing active or selective responses in the arithmetic and memory conditions separately and χ^2 test results of the frequencies of sites between different categories. Electrodes included in each category were statistically significant at $p < .05$, FDR corrected.

the spatial orientation and arithmetic processing were mostly centered closer to the IPS.

DISCUSSION

In our study, we leveraged the anatomical precision of ECoG recordings and the high signal-to-noise ratio of the HFB signal to explore the functional architecture of the human PPC in individual human participants. We showed that only 98 of 179 PPC sites were activated during any of the probed conditions (visuospatial attention, arithmetic, and autobiographical memory) and that the activated sites were spread across the PPC in a patchy and mosaic form in a given individual brain. About 40% of PPC recording sites did not show any significant engagement during any of the probed cognitive conditions in our experiments. We explain this by the lack of visually guided behavioral task in our study (e.g., grasping or reach-related activity; Culham & Kanwisher, 2001). Moreover, only 51 of 179 PPC sites responded selectively in one of the three tested functions, whereas most sites had overlapping activities. A large proportion of the selective sites were activated during visuospatial attention tasks, whereas only three and eight singular sites were engaged selectively in the arithmetic and memory retrieval conditions, respectively. The results shed new light on the functional organization of the human PPC and provide further evidence for not only generic overlapping but also nonoverlapping and selective mode of responses in the human PPC.

The most salient finding in our study pertains to our observation that if a site in the PPC shows preferential responses during attention to contralateral visual field, there is a higher probability that the site is highly responsive to numerical stimuli, indicating a closer connection between spatial and numerical processing. By comparison, if a site within the PPC is activated to visuospatial stimuli in both ipsilateral and contralateral visual fields, it is likely that the site is also active during numerical and memory conditions, which may reflect generic attention demand during the cognitive tasks. These findings are relevant to the ongoing discussions in the extant literature about a possible link between representation of space and numbers in the brain (see, e.g., Mathieu et al., 2018; Knops, Thirion, Hubbard, Michel, & Dehaene, 2009; Hubbard, Piazza, Pinel, & Dehaene, 2005; Dehaene, Piazza, Pinel, & Cohen, 2003; Fischer, 2001). Our findings are also in line with single-neuron studies showing that neurons encoding quantity information overlap with the parietal circuitry involved in spatial representations especially in the IPS (Nieder & Miller, 2004; Andersen & Buneo, 2002). Although the main purpose of our current study was to determine if a given PPL neuronal population has overlapping responses during spatial and numerical conditions, our experiments were not designed to address the nature of computations that could explain such an overlap. Moreover, various experimental tasks were used across

individuals, and although this may not be a significant problem for arithmetic tasks (because the main variable was the mode of presentation, simultaneous or sequential), there could be an issue with the visuospatial attention tasks whose contents varied across participants. To mitigate this problem, we made sure to include in our analyses only the parameters that were common across the tasks. For instance, in the visuospatial attentional tasks, we only focused on responses within a time window of 200–400 msec after the cue onset, which would be the time when the participants' attention was cued on a specific location in the visual field—to exclude the potential artifacts of early nonselective activity to the variable visual stimulus. Future studies with carefully designed tasks are needed to address the details of overlapping cortical responses during visuospatial attention and various numerical conditions (e.g., addition vs. subtraction, or large vs. small magnitude processing).

Using episodic memory as an ancillary condition in our experiments gave rise to some interesting results that are in keeping with emerging studies, suggesting that memory retrieval requires contribution from the PPC with specific subregions displaying distinct roles (Burianova, McIntosh, & Grady, 2010; Wagner, Shannon, Kahn, & Buckner, 2005). Specifically, the SPL tracks retrieval decision uncertainty by showing higher activation during low- than high-confidence judgments. The IPS is responsible for evaluating perceived memory strength and familiarity, whereas the AG only engages in episodic recollection no matter what the participant is recollecting or the degree of memory familiarity (Parvizi & Wagner, 2018). Consistent with the previous findings, our results showed that 26% of the PPC sites, mostly in the SPL and AG, were active in the autobiographical memory condition. Moreover, we found 15 sites in the PPC that showed selective responses to autobiographical memory, and seven of them also showed general activation in the visuospatial attention (but not visuospatial orientation) task, which might be related to attentional demand in memory retrieval. More importantly, we did not find any site that showed preference to contralateral visual field as well as selective responses during the memory condition. These findings are consistent with the notion of episodic memories being associated more with temporal rather than spatial representations (Bueti & Walsh, 2009).

Overall, our results provide a mesoscale level of information about functional anatomical organization for the neurophysiological activity within the human brain during a set of cognitive operations by providing within-individual and "within native anatomical brain space" information. Our results based on rare intracranial recordings from the human PPC provide direct electrophysiological evidence for overlapping responses during visuospatial orientation (visuospatial attention to contralateral visual field items) and arithmetic processing. Our findings also provide hypotheses that can be tested directly in the future using specifically designed experimental tasks. For

instance, what remains to be determined is what extent selective HFB responses in the arithmetic-related sites are causally related to processes such as representation of the numerical values of the operands, working memory of numerical values, arithmetic rules, or accumulation of numerical evidence.

Diversity in Citation Practices

A retrospective analysis of the citations in every article published in this journal from 2010 to 2020 has revealed a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .408, W(oman)/M = .335, M/W = .108, and W/W = .149, the comparable proportions for the articles that these authorship teams cited were M/M = .579, W/M = .243, M/W = .102, and W/W = .076 (Fulvio et al., *JoCN*, 33:1, pp. 3–7). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance.

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