# Motor role of parietal cortex in a monkey model of hemispatial neglect

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**Parietal cortex is central to spatial cognition. Lesions of parietal cortex often lead to hemispatial neglect, an impairment of choices of targets in space. It has been unclear whether parietal cortex implements target choice at the general cognitive level, or whether parietal cortex subserves the choice of targets of particular actions. To address this question, monkeys engaged in choice tasks in two distinct action contexts—eye movements and arm movements. We placed focused reversible lesions into specific parietal circuits using the $GABA_A$ receptor agonist muscimol and validated the lesion placement using MRI. We found that lesions on the lateral bank of the intraparietal sulcus [lateral intraparietal area (LIP)] specifically biased choices made using eye movements, whereas lesions on the medial bank of the intraparietal sulcus [parietal reach region (PRR)] specifically biased choices made using arm movements. This double dissociation suggests that target choice is implemented in dedicated parietal circuits in the context of specific actions. This finding emphasizes a motor role of parietal cortex in spatial choice making and contributes to our understanding of hemispatial neglect.**

spatial cognition | LIP | attention | choice | decision

Parietal lesions often lead to deficits of the selection of behaviorally relevant targets in space, collectively referred to as hemispatial neglect (1–4). Hemispatial neglect has commonly been diagnosed by presenting a patient with two visual targets at the same time, one in each visual hemifield (1, 5, 6). Neglect patients show difficulties with detecting or directing an action to the target presented in the hemifield contralateral to the lesioned hemisphere (2–4). The failure to detect or direct an action to a target in the contralesional hemifield, also termed "extinction," is conditioned on the presence of the competing second target; detecting or directing an action to a single visual target usually incurs little or no difficulty to a neglect patient (6, 7) or to a monkey neglect model (8). The competitive, relativistic nature of the extinction phenomenon has been taken as evidence that parietal cortex is involved in choosing behaviorally relevant targets in space (9).

A lingering question (10–13) has been whether parietal cortex acts as a cognitive module that performs the general function of spatial choice making (5, 14), or whether parietal cortex implements choices between targets in the context of specific upcoming actions (13, 15, 16). This debate remains, for the most part, unresolved (13). Only few parietal lesion studies explicitly tested for biases in spatial choice making (8, 15, 17). Of these, only one study (15) specifically aimed to distinguish the perceptual from motor deficits in spatial choice making. However, because this study used human lesion patients, it was impossible to control for the precise locus and extent of each lesion, which complicates the interpretation of the results (18, 19).

Here, we probe the role of parietal cortex in spatial choice making by engaging monkeys in tasks in which they chose between two visual targets under one of two action contexts—eye movements (saccades) and arm movements (reaches). If an inactivation of a given region biased choices for both movement types, this would present evidence for a general perceptual role. On the other hand, a choice bias specific to the saccade or the reach context would suggest a motor basis. While animals performed the tasks, we selectively inactivated two regions of parietal cortex—the lateral intraparietal area (LIP) and the parietal reach region (PRR), using the $GABA_A$ receptor agonist muscimol. We induced targeted and focused reversible lesions in a given region and validated the placement of each lesion using MRI scans. We found that lesions of specific parietal circuits (LIP/PRR) biased choices made using specific actions (saccades/reaches). This suggests that dedicated parietal circuits underlie the selection of targets of specific actions.

## Results

Deficits of spatial choices associated with parietal lesions have commonly been tested in the clinic by simultaneously presenting visual targets or symbols in opposite parts of the visual field (1, 5). In laboratory settings, researchers have modified this task by introducing a delay between the onsets of the two targets (6, 8, 15, 17, 20). Specifically, one target appears in the right (left) part of the screen. After a brief variable delay, a second target appears on the left (right). A subject must select the target that appeared earlier. The advantage of this additional control is that in the limit—when the delay is long—the task reduces to a task in which only one target is presented on the screen; by manipulating the delay duration, one can probe the continuum between a simple one-target and a two-target choice task (6). In a critical extension of this extinction task, our subjects were instructed to select the earlier target using one of two effectors—a saccade or a reach—based on a color cue (Fig. 1).

Given the two distinct effector contexts, we investigated the role of particular parietal circuits in target choice. We reversibly inactivated circuits on the lateral bank of the intraparietal sulcus (LIP). We targeted LIP because LIP lesions have been shown to

### Significance

**Humans and animals often choose between targets in space. Parietal cortex is known to be critical to this function. However, the exact role of parietal cortex in spatial choice remains controversial. Does parietal cortex implement choices at the general cognitive level, or are the choices made in the context of specific upcoming actions? We placed focused reversible lesions into specific parietal circuits of monkeys making choices between two targets. Lesions of specific circuits only affected choices made using specific actions: lesions of lateral intraparietal area (LIP) affected eye movements but not reaches, while lesions of the parietal reach region had converse effects. This illuminates the nature of spatial choice in parietal cortex, and suggests that choice is implemented in dedicated parietal circuits, each responsible for a specific class of actions.**

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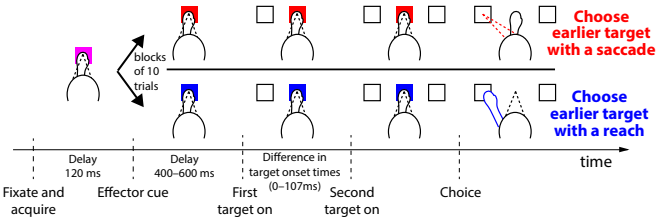


**Fig. 1.** Choice in the context of two distinct actions. In this task, a monkey acquired a central target, which changed color, in blocks of 10 trials, to either red or blue. The red (blue) color instructed the animal to make a subsequent choice using a saccade (reach). After a delay, a white target appeared in the left (right) part of the screen. Following a variable delay (0–107 ms), a second white target appeared in the right (left) part of the screen. To receive a reward, the animal had to select the target that appeared earlier, using the instructed effector.

bias animals' choices in choice tasks (8, 17). We also reversibly inactivated circuits on the medial bank of the intraparietal sulcus (PRR) to probe the contribution of these circuits to spatial choice making. We injected a small amount of muscimol (mean injected volume, 1.0 μL; range, 0.5–2.0 μL; 8 μg/μL; *SI Appendix*, Table S1), a $GABA_A$ receptor agonist, into a given region. We injected a small amount to be sure that there was no spread of the drug to outside of the region of interest and confirmed this by directly visualizing the injection using MRI (Figs. 2*A* and 3*A*, and *SI Appendix*, Table S1).

We found that LIP inactivations bias animals' choices only when animals choose using a saccade (Fig. 2*B*). As in previous studies that have used a saccade as the response modality, targets in the contralesional hemifield are less likely to be selected, and the effect is most prominent when the correct (earlier) target appears in the contralesional hemifield (8, 15, 17). The choice bias during saccade choices was present in both monkeys (Fig. 2*B*), and in most of the individual sessions (Fig. 2*C*). Over the 19 sessions, the average difference in the percentage of the contralesional target choices between inactivations and controls was −7.6% (Fig. 2*D*), and this effect was significant ($P < 0.0001$, $n = 19$, $t$ test, inactivations compared with controls).

Critically, in the same task, the animals' choices in the trials in which they selected a target using a reach while maintaining fixation remained largely intact (blue in Fig. 2). Specifically, during choices made using reaches, the average difference in the percentage of the contralesional target choices between inactivations and controls was +1.4%, a nonsignificant value ($P = 0.14$, $n = 19$). The difference between the saccade and reach effects (red versus blue in Fig. 2*D*) was significant ($P < 0.0001$, $n = 19$, paired $t$ test).

In contrast to LIP, PRR inactivations (Fig. 3*A*) produced a reverse deficit with respect to the choice effector. Specifically, PRR lesions caused a small target selection bias during choices made using reaches (blue in Fig. 3*B*). Over the 11 sessions (Fig. 3*C*), the inactivation effect was a −4.2% difference (Fig. 3*D*; $P = 0.04$, $n = 11$, $t$ test, inactivations compared with controls). In contrast to the marked effect in LIP, there was no target selection bias during saccadic choices in PRR (+1.1%, $P = 0.54$, $n = 11$). The difference between the reach and saccade effects (blue versus red in Fig. 3*D*) was significant ($P = 0.02$, $n = 11$, paired $t$ test).

We further evaluated the effects of inactivation relative to the effects in sham inactivation sessions. The sham inactivation sessions were identical to the inactivation sessions except that no drug was injected. Specifically, in this analysis, instead of evaluating the effects relative to control, i.e., as (inactivation − control), we evaluate the effects relative to the effects in the sham sessions, i.e., as (inactivation − control) − (sham inactivation − sham control). This analysis provides additional controls beyond that provided by the simpler analysis. For example, it controls for the fact that inactivation trials occurred later in each session than control trials. The results are similar to those of the simpler analysis, with if anything slightly greater effector specificity. In particular, in LIP, there was a −9.2% decrease of the contralesional target choices for saccades ($P < 0.0001$, $n = 14$; there were no sham data for the initial five sessions in monkey D) and +1.5% ($P = 0.19$) increase for reaches. The difference between the saccade

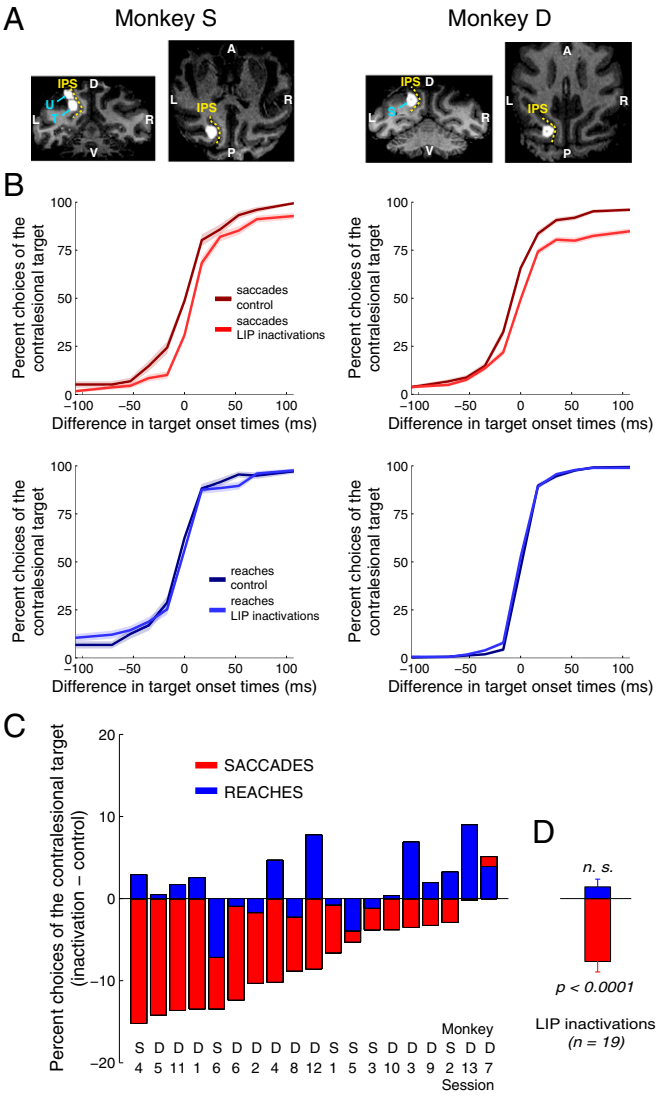


**Fig. 2.** LIP inactivations bias choices specifically made using saccades. (*A*) Anatomical MR scans following muscimol plus $MnCl_2$ injections. The contrast agent $MnCl_2$ indicates the spread of the drug as a white spherical region. The figure gives the loci (S, T, U) of the LIP lesions performed in each monkey. The left and right images for each monkey represent the coronal and transverse views, respectively. See *SI Appendix*, *SI Methods* and Table S1, for details. IPS, intraparietal sulcus. A, anterior; P, posterior; D, dorsal; V, ventral; L, left; R, right. (*B*) Mean ± SEM percentage of choices of the contralesional target as a function of the delay between the onset of the contralesional and the ipsilesional target, separately for control sessions (dark colors), lesions (light colors), and saccade (red) and reach (blue) choices. (*Left*) Monkey S. (*Right*) Monkey D. The figure shows all of the individual choices that a monkey made. (*C*) The difference in the percentage of choices of the contralesional target (inactivation minus control) for each individual session in each monkey, separately for saccade choices (red) and reach choices (blue). (*D*) Mean ± SEM over the individual session data points shown in *C*. The *P* value is the statistical outcome of the paired *t* test (control versus inactivation) performed on the data of each effector; n.s.: $P > 0.05$.

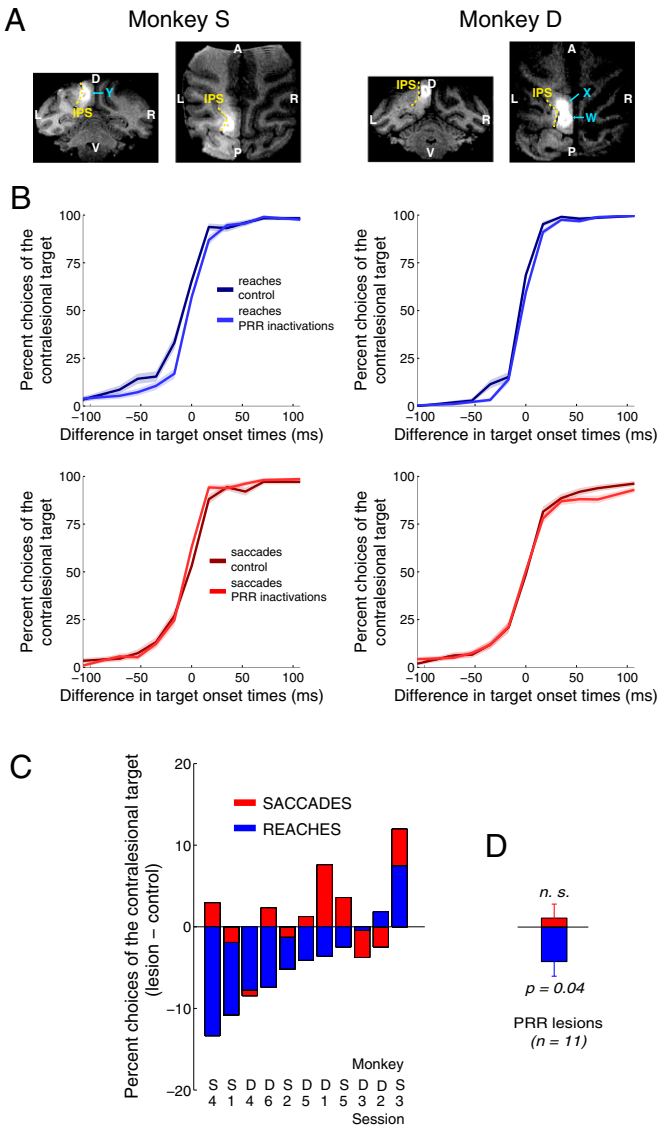


**Fig. 3.** PRR inactivations bias choices specifically made using reaches. Same format as in Fig. 2 for the effects during PRR lesions. (*A*) Anatomical MR scans following muscimol plus MnCl2 injections. (*B*) Mean ± SEM percentage of choices of the contralesional target as a function of the delay between the onset of the contralesional and the ipsilesional target. (*C*) The difference in the percentage of choices of the contralesional target (inactivation minus control) for each individual session in each monkey, separately for saccade choices (red) and reach choices (blue). (*D*) Mean ± SEM over the individual session data points shown in *C*.

and reach effects (−10.7%) was significant ($P < 0.0001$). In PRR, there was a −4.9% decrease in the contralesional target choices for reaches ($P = 0.10$, $n = 11$) and a +1.6% ($P = 0.29$) increase for saccades. The difference (6.5%) was significant ($P = 0.023$).

We next investigated the effects of the inactivations on the choice behavior in more detail, separately for each session. To do so, we fitted the choice data (Figs. 2*B* and 3*B*) with a logistic function. The logistic function features two parameters (see *Methods* for details). The first parameter, *shift*, is the temporal delay between the appearance of the two targets which results in them being selected in equal proportion. An increase in *shift* following an inactivation compared with control (a "rightward" shift) could indicate a lag in the registration of the contralesional target, such that, all else being equal, it is less likely to be chosen. The second parameter, *slope*, defines the psychometric performance of the animal. A steeper *slope* would indicate an improvement in the ability to discriminate between the target onset times. If an inactivation led to a decrease in the *slope*, this would suggest that the inactivation deteriorated the animal's performance.

We fitted the logistic function separately for the control and inactivation choice data of each session, separately for saccade choices, reach choices, and LIP and PRR. To quantify the effects induced by an inactivation in a given session, we report the changes—inactivation minus control—in the fitted parameter values. The mean effects for the individual conditions are reported in Table 1. Bold entries denote significant effects ($P < 0.05$, paired $t$ test, inactivation versus control). These data corroborate the findings reported in Figs. 2 and 3. In particular, lesions of LIP induced a significant ($P < 0.001$, paired $t$ test, $n = 19$) rightward shift of the psychometric curve when a choice is made in the saccade decision context. The shift was significant in both monkey S ($P = 0.028$, $n = 6$) and in monkey D ($P = 0.003$, $n = 13$). The shift was positive in 17 of 19 (89%) of the LIP inactivation sessions. We further performed a randomization test (*Methods*) to establish the significance of the shift in each individual session. This test revealed that the shift was significant ($P < 0.01$) in 13 of 19 (68%) sessions. Of the 13 significant shifts, 12 were positive.

In contrast, LIP lesions did not induce a significant shift of the psychometric curve in the reach decision context ($P = 0.58$, $n = 19$). Only three sessions (16%) showed a significant positive shift, and five sessions (26%) showed a significant negative shift.

In PRR, there was a weak but significant positive shift in the reach decision context ($P = 0.036$, $n = 11$). The shift was significantly positive in 5 of 11 (45%) of the sessions, and significantly negative in 2 of 11 (18%) of the sessions. There was no shift in the saccade context in PRR ($P = 0.64$, $n = 11$).

The lesions did not significantly change the slope (Table 1). The lesions therefore did not significantly affect the discriminability between the temporal differences in the target onsets.

A shift of about 10 ms (Table 1) in the perceived target onset following an inactivation may seem small. However, the effect is in fact considerable given the animals' high sensitivity to the target onset times in this task. A fit to the psychometric curve constructed using all choice data revealed a slope of 0.089 $ms^{-1}$. Given this steep slope, a delay value of 10 ms, compared with 0 ms, corresponds to a change in the proportion of choices of the rightward target from 50% (0 ms) to 70.8% (10 ms). A 5-ms delay would correspond to 60.9% of choices of the rightward target. Almost exclusive rightward choices (93.4%) would result from a shift of just 30 ms. The reported effect of a 10-ms shift is therefore substantial given the high performance of our animals

**Table 1. Logistic fits to the data: Inactivation minus control**

| | | LIP | | PRR | |
|---|---|---|---|---|---|
| | | Saccades | Reaches | Saccades | Reaches |
| Both monkeys | Shift | **10.2** | −0.5 | 1.1 | **5.5** |
| | Slope | −0.01 | −0.02 | −0.01 | −0.01 |
| Monkey S | Shift | **10.7** | 1.7 | −0.8 | 8.5 |
| | Slope | 0.00 | −0.02 | −0.01 | 0.00 |
| Monkey D | Shift | **9.9** | −1.6 | 2.7 | 3.0 |
| | Slope | −0.01 | −0.02 | −0.01 | −0.03 |

The data in Figs. 2*B* and 3*B* were fitted with a logistic function with two parameters, shift (in milliseconds) and slope (per millisecond); see *Methods* for details. The fits were performed separately for the inactivation and the control data; the difference between the two is shown. The data are presented separately for LIP, PRR, saccade trials, reach trials, and for the individual animals. Bold entries denote significant effects [$P < 0.05$, paired $t$ test, inactivation versus control; LIP: $n = 19$ sessions (monkey S, $n = 6$; monkey D, $n = 13$); PRR: $n = 11$ sessions (monkey S, $n = 5$; monkey D, $n = 6$)].

in this extinction task. We further found that the effector-specific effects in LIP and PRR increase as a function of the time following an injection (*SI Appendix*, Fig. S5), so that the maximum lesion effects were even larger than what we report here.

We also fitted the data with a more complex, four-parameter sigmoidal model (*SI Appendix*, Table S3). Besides the two-parameter fit described above, this model features additional two parameters: *vertshift* and *vertscale*. The former parameter models a shift of the psychometric curve on the vertical axis. The latter parameter models a scale of the psychometric curve on the vertical axis. Although there may be dependencies between the four parameters, the resulting fits generally led to the same insights: LIP lesions, in the saccade context, caused a rightward shift of the psychometric curve (5.3 ms, $P = 0.0069$, $n = 19$; monkey S, 6.5 ms, $P = 0.14$, $n = 6$; monkey D, 4.8 ms, $P = 0.035$, $n = 13$). For saccades in LIP, there was also a significant effect of *vertscale* (–0.07, $P = 0.006$; monkey S, –0.06, $P = 0.17$; monkey D, –0.07 ms, $P = 0.023$), which indicates a scaling down of the psychometric curve following an inactivation. Both the rightward shift and the vertical downscale for saccades following an LIP inactivation are apparent from the raw data plots in Fig. 2*B*. Other changes were not significant in this more complex model ($P > 0.05$), although was a trend for a rightward shift in PRR in the reach context (4.8 ms; $P = 0.10$, $n = 11$).

In line with previous studies, the inactivations also had small effects (*SI Appendix*) on reaction time (17, 21) and reach endpoints (22). Also in accord with previous studies, there were no appreciable effects on movement duration or error rates (*SI Appendix*).

Together, the inactivations of specific parietal circuits resulted in action-specific biases in spatial choices. Critically, these biases occurred in an extinction task that has been commonly interpreted as detecting general deficits in spatial selection (5, 14). However, our lesions of specific parietal circuits revealed action-specific deficits in spatial choices. This strongly suggests that dedicated parietal circuits help to select targets using specific movement types.

## Discussion

It has been debated (15, 18, 23–27) whether parietal cortex helps to choose a target in space regardless of how that target will be used, or whether target choice is implemented in specific parietal circuits, where the circuits that are used depend on the action that will be performed. We inactivated particular parietal circuits in choice tasks in two effector contexts to provide an answer. The results support the latter hypothesis.

Hemineglect deficits in spatial choices have often been tested for by simultaneously or almost simultaneously appearing visual targets or symbols in opposite parts of the visual field (1, 5, 6, 8, 15, 17, 20). The difficulty of hemineglect patients to detect or direct an action to a target in the contralesional hemifield ("extinction") is conditioned on the presence of the competing second target; detecting or directing an action to a single visual target usually incurs little or no difficulty to a neglect patient (6, 7). This is supported by analogous findings in nonhuman primates following LIP lesions (8, 28)—when animals are instructed to make a movement to a single target, there is no detectable effect on behavior (8) or only a minimal effect on reaction time (28). Thus, to reliably detect neglect-related deficits, it is critical to use a task that involves choice between two targets (8, 17).

To tell apart the perceptual and motor bases of the choice-related deficits, we applied this choice task in two action contexts—saccadic and reach contexts—while inactivating specific parietal circuits. We found that LIP inactivations specifically biased spatial choices when the choices were made using saccades, whereas PRR inactivations showed a reach-specific choice bias. This double dissociation is surprising considering the predominantly held view on the nature of hemispatial neglect. In particular, in extreme cases, patients may read only one-half of a sentence, draw only one-half of an image, or shave only one-half of their face (3, 4). Such profound cases have led to the propositions that hemineglect may be based on general deficits of spatial perception or attention (5, 14). Surprisingly then, our results suggest action-based target selection deficits wherein the selection of a particular action is represented in a specific parietal circuit.

Previous clinicopathological studies in various tasks report effects of parietal lesions on certain parameters of eye movements (15, 29–31), on certain parameters of hand movements (12, 16, 32), and possibly on spatial perception in general (5, 14). Our two-context choice paradigm and the targeted lesion approach provide a way to reconcile these ambiguous clinicopathological findings. Our data reveal that paying close attention to the affected region is critical. Millimeter differences in the lesion locus may profoundly change the signs. In particular, lesions confined to the lateral bank of the intraparietal sulcus (IPS) affect saccade-based choice behavior. Lesions just a few millimeters across the IPS on its medial bank influence reach-based choice behavior. Thus, when a lesion is confined to a specific parietal circuit (LIP or PRR), one specifically observes choice deficits in the context of a specific action. For the case of lesions that commonly affect a large volume of brain issue, instead of a confined parietal circuit—say a lesion that impacts the human homologs of both LIP and PRR—our data predict an impairment of choices made both using saccades and reaches, and possibly other effector systems subserved by the circuits in the affected region as well. Such extensive lesions may thereby impair spatial selection in a way that appears to be generic or action independent (5, 14).

Nonetheless, our results should be taken as a model of human hemineglect with care. First, it is not clear whether the particular parietal circuits we study in monkeys exist in and perform similar functions in humans [although there is evidence that this may be the case (15, 33)]. Second, it is not clear whether a lesion mediated by muscimol—which silences excitatory projection neurons by increasing the level of inhibitory input on those cells—has a similar effect on behavior as brain damage that affects both inhibitory and excitatory cells, as well as any fibers passing through a region [although the effect may indeed be similar (15)].

The focal pharmacological inactivations in this study had only modest influence on the animals' choices. This is likely due to three reasons. First, we performed small inactivations to make sure that the inactivations remained within a single region. These lesions targeted only a small fraction of each area. It is therefore not surprising that the induced deficits were not severe. Second, we found that the effects increase with increasing time following an injection (*SI Appendix*, Fig. S5). This suggests that the effects we report would be stronger had we waited longer (34) following each injection before starting to collect data. Third, LIP and PRR are certainly not the only actors in the selection of targets in space. These parietal regions likely represent only nodes in a larger spatial selection network that includes frontal and cingulate cortices (35). This is supported by findings in humans where even extensive parietal lesions may produce only modest deficits in spatial choice making (15).

Related to the last point, parietal cortex itself may contain, along with action-specific regions like LIP and PRR, other regions that implement spatial selection in a general, action-independent manner. We investigated the roles of only two regions, and we did so in a monkey model that may differ substantially from human parietal cortex in both anatomical and functional properties (36).

A point to keep in mind is that certain actions (such as eye movements) might be linked to certain cognitive processes (such as attention) more tightly than other actions. If this is the case, then our results might equally well be described through particular cognitive processes instead of through particular actions. However, the exact nature of the putative links between particular actions and particular cognitive processes is unknown and difficult to establish. As such, we describe the results within the frame of what can be directly observed, that is, with respect to particular actions.

Our findings provide evidence for an action-based, embodied neural architecture of spatial choice making, an alternative to a

classical cognitive, action-independent architecture (37). In the classical architecture, useful for making generic choices, an abstract choice-related variable is first computed in a central, generic circuit (38), and subsequently routed to a specific motor circuit for execution. In comparison, in the action-based, embodied architecture (23, 25–27), the choice process runs on circuits devoted to executing particular kind of movement. This architecture therefore does not require postselection routing to trigger the desired movement. An intermediate possibility is that the signals we see in LIP and PRR may reflect the intermediate output of a choice circuit that "leaks out," while the choice is still evolving, onto the movement-planning circuit that will be used to implement that choice. Both the fully embodied architecture and the intermediate possibility have the advantage that they may allow animals to respond quickly and reduce errors associated with the late choice of a movement effector. This can be evolutionarily advantageous when making urgent choices such as where to turn, where to look, or which object to reach for. Embodied architecture of this sort may also be useful in complex motor tasks, such as when deciding to which side to move when a tennis opponent positions herself to play a volley. In other decision contexts, embodied architecture would not be applicable, for example, when choosing a meal from a menu (38), or when choosing a spouse.

In summary, we induced biases in spatial choices by inactivating specific parietal circuits. Our choice task featured two response contexts, which allowed us to disambiguate the perceptual and motor roles of specific parietal circuits in choice making. The results suggested that choices made using specific actions were represented in specific parietal circuits. Representing the process of arriving to a choice in the same circuit that is devoted to planning and execution of a particular action can be advantageous in cases when humans or animals must make fast and specific decisions such as where to turn, where to look, or where to reach. The data further have a diagnostic or prognostic utility to future investigators or clinicians, suggesting that deficits in spatial choice making should be assessed or interpreted in a careful consideration of the particular parietal region(s) affected.

## Methods

**Subjects.** Two adult male rhesus monkeys (*Macaca mulatta*; monkey S, 7 kg; monkey D, 7 kg) participated in this study. The animals sat head-fixed in a custom-designed monkey chair (Crist Instrument) in a completely dark room. Visual stimuli (squares of 2.3° × 2.3°) were backprojected by a cathode ray tube projector onto a custom touch panel positioned 25 cm in front of the animals' eyes. Eye position was monitored by a scleral search coil system (CNC Engineering). Monkey S was trained to reach with its right arm, and monkey D with its left arm. In each monkey, we inactivated and recorded from the hemisphere that was contralateral to the reaching arm. All procedures conformed to *Guide for the Care and Use of Laboratory Animals* (39) and were approved by the Washington University Institutional Animal Care and Use Committee.

**Task.** We trained the monkeys in an extinction task that has been used to measure biases in choice in previous studies (6, 8, 15, 17, 20, 40). Briefly, in this task, monkeys first acquired a fixation target. After a short delay, a first target (gray square of 0.5° × 0.5°) appeared in the left (right) part of the screen, 12 visual degrees away from the center of fixation. After a random delay [∈ {0, 17, 35, 53, 71, 107} ms (multiples of the period corresponding to the 56-Hz screen refresh rate)], a second target, of identical parameters, appeared in the right (left) part of the screen. Once presented, both targets remained present until a choice was made. To receive a liquid reward, the animal had to make a saccade to the target that was presented first. Rewards were delivered on only 60% of correct trials, to decrease the reliability of the feedback that may make an animal compensate for a deficit during an inactivation. In a critical extension of the extinction task, in our task, the color of the central target instructed the animal to choose a target using either a saccade (red cue) or a reach (blue cue). When selecting a peripheral target using a saccade, the animal had to keep his hand on the central target; when selecting a target using a reach, the animal had to keep fixating the central target until the reach was completed. The color changed every 10 trials.

**Inactivation Procedure.** We inhibited the activity of neurons in parietal circuits using the $GABA_A$ receptor agonist muscimol. To ensure that our lesions targeted a specific parietal circuit, we performed small, focal injections (mean, 1.0 μL; range, 0.5–2.0 μL; *SI Appendix*, Table S1). The injections targeted either a single locus or two loci in a given area (*SI Appendix*, Table S1). The injections included the magnetic resonance contrast agent $MnCl_2$ (165 μg/μL), which was used to verify the injection loci using anatomical MR scans. We collected data first after we were able to specifically target LIP or PRR (*SI Appendix*, Fig. S1). Each inactivation session started with a "control" block of 1,200–1,400 trials (the exact number depended on the monkey and its current weight). Following the control block, we lowered the injection cannula into the specific region and depth (*SI Appendix*, Table S1), and injected the specified amount of muscimol (*SI Appendix*, Table S1; 8 μg/μL solution) into the tissue at a rate of 0.1 μL/min. For the LIP lesions, we targeted ventral LIP (LIPv) because LIPv, in contrast to dorsal LIP (LIPd), seems to mediate both oculomotor and higher order (e.g., attentional) processes (21). Following the injection, we waited 10 min for the drug to affect the function of the $GABA_A$ receptors. Subsequently, we collected data in an "inactivation" block, which was identical to the control block, and also comprised 1,200–1,400 trials.

The inactivation sessions were interleaved, on a daily basis, with sham inactivation sessions. A sham session involved the same procedure as an inactivation session, with the exception that the cannula was not physically lowered into the tissue. The sham sessions allowed monitoring of the monkeys' choice biases on a daily basis. We made sure that there were no spurious effects in the sham session on the day before an inactivation session day. Specifically, we performed an inactivation session only when the monkey's choice proportions during the control block and the inactivation block during the sham session on the previous day did not significantly differ ($P > 0.05$, proportion test) for saccade and reach choices. To maximize the number of collected trials, we collected the inactivation data on a day separate from the control data in the first five sessions in monkey D (i.e., there were no sham data for the initial five sessions in monkey D). To minimize the possible influence of day-to-day variability, in all subsequent sessions, the control and lesion data were collected within the same day.

We plot effects in this study as the difference between a given behavioral measure during the inactivation block minus the measure during the control block, i.e., as (inactivation − control). Similar results are obtained when we plot the effects relative to the sham session effects, i.e., as (inactivation − control) − (sham inactivation − sham control).

**Parameter Fits and Sessionwise Statistical Analyses.** To learn about specific effects of the inactivations, we fitted the data in Figs. 2*B* and 3*B* with logistic functions. The fit has two parameters, *slope* and *shift*, as follows:

$$P(x) = 1/(1 + \exp(-slope(x - shift))),$$

where $x$ is the delay between the onset of the two targets, and $P(x)$ is the probability of choosing the rightward target (i.e., the individual points of each psychometric curve).

The parameters were fitted to the psychometric curves using nonlinear minimization (function fminsearch in Matlab), minimizing the squared error between the fitted and the actual psychometric curves.

We also tested a more complex fit, featuring four parameters—*slope*, *shift*, *vertscale*, and *vertshift*—as follows:

$$P(x) = vertscale/(1 + \exp(-slope(x - shift))) + vertshift.$$

We determined the significance of an effect (a fitted parameter) between the control and inactivation psychometric curves on a sessionwise basis using a bootstrapping procedure. In this procedure, a set of 1,000 control psychometric curves was generated from the control data from each session. Each of these control curves was generated by drawing choice data randomly, with replacement, from the original set of control session choice data, for a given value of $x$. These 1,000 sets of randomly chosen data were then fitted in exactly the same way as the original psychometric data were fitted, using both the two and four parameter models (see above). This resulted in a distribution of 1,000 values for each fit parameter. Next, for each parameter, we computed the mean and the SD of the 1,000 values. Finally, we applied the same fitting procedure to the inactivation data and compared each individual inactivation fit parameter to the distribution of the corresponding control fit parameter. In particular, for each inactivation parameter, we computed the probability ($P$ value) that it might belong to (could have been drawn from) the control distribution.

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