Spatial Updating in Monkey Superior Colliculus in the Absence of the Forebrain Commissures: Dissociation Between Superficial and Intermediate Layers

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Submitted 30 July 2009; accepted in final form 1 July 2010

Dunn CA, Hall NJ, Colby CL. Spatial updating in monkey superior colliculus in the absence of the forebrain commissures: dissociation between superficial and intermediate layers. J Neurophysiol 104: 1267–1285, 2010. First published July 7, 2010; doi:10.1152/jn.00675.2009. In previous studies, we demonstrated that the forebrain commissures are the primary pathway for remapping from one hemifield to the other. Nonetheless, remapping in lateral intraparietal cortex (LIP) across hemifield is still present in split brain monkeys. This finding indicates that a subcortical structure must contribute to remapping. The primary goal of the current study was to characterize remapping activity in the superior colliculus in intact and split brain monkeys. We recorded neurons in both the superficial and intermediate layers of the SC. We found that across-hemifield remapping was reduced in magnitude and delayed compared with within-hemifield remapping in the intermediate layers of the SC in split brain monkeys. These results mirror our previous findings in area LIP. In contrast, we found no difference in the magnitude or latency for within- compared with across-hemifield remapping in the superficial layers. At the behavioral level, we compared the performance of the monkeys on two conditions of a double-step task. When the second target remained within a single hemifield, performance remained accurate. When the second target had to be updated across hemifields, the split brain monkeys’ performance was impaired. Remapping activity in the intermediate layers was correlated with the accuracy and latency of the second saccade during the across-hemifield trials. Remapping in the superficial layers was correlated with latency of the second saccade during the within- and across-hemifield trials. The differences between the layers suggest that different circuits underlie remapping in the superficial and intermediate layers of the superior colliculus.

INTRODUCTION

Visual stability depends on the ability to integrate incoming visual information from the retina with outgoing motor signals that control where the eyes are pointed. This integration of visuals and motor signals occurs in many brain regions. Neurons in lateral intraparietal cortex (LIP), frontal eye fields (FEFs), extrastriate cortex, and the superior colliculus (SC) update stimulus traces by remapping or shifting their receptive fields at the time of an eye movement (Duhamel et al. 1992; Goldberg and Bruce 1990; Hallett and Lightstone 1976; Mays and Sparks 1980a; Nakamura and Colby 2002; Sommer and Wurtz 2006; Walker et al. 1995). This updating reflects a transfer of visual information from neurons that encode a salient location before a specific eye movement to neurons that will encode that location after the saccade.

Many neurons that remap can receive information representing multiple areas of visual space (Heiser and Colby 2006). How is remapped information transferred from one side of the brain to the other? One possible pathway is through direct cortico-cortical connections. Specifically, when stimulus traces are updated across hemifields, information could be transferred through the forebrain commissures—the corpus callosum and the anterior commissure. Berman and colleagues tested this possibility by transecting the forebrain commissures (Berman et al. 2005, 2007; Heiser et al. 2005). They examined the effects of this transection on performance in a double-step task, a task that requires spatial updating, and on remapping activity in LIP.

The double-step task requires that spatial information be updated when the eyes move. Both humans and monkeys are able to perform the double-step task accurately (Bender 1989; Gnadt and Andersen 1988; Goldberg and Bruce 1990; Hallett and Lightstone 1976; Mays and Sparks 1980a; Medendorp et al. 2006; Ray et al. 2004). To complete the task successfully, the monkey must remember the order and locations of the two saccade targets. The memory of the second location must be adjusted so that it is relative to the endpoint of the first saccade. In other words, the representation of the second target must be updated to account for the first saccade.

To test the hypothesis that the forebrain commissures were required for updating behavior across-hemifields, performance on two versions of the double-step task was compared (Berman et al. 2005). When the second target location remained within the same hemifield before and after the initial saccade, split brain monkeys performed accurately. In contrast, monkeys were initially unable to perform the double-step task when the visual information was in the opposite hemifield after the first saccade. Surprisingly, recovery began almost at once. Monkeys ultimately recovered to the point where they could correctly perform the task when it required across-hemisphere remapping of visual information. Berman et al. (2005) concluded that the forebrain commissures are not necessary for behavior dependent on spatial updating. At the single neuron level, Heiser and colleagues (2005) asked whether remapping was still present in area LIP in the split brain monkeys. They recorded from LIP neurons while the monkeys performed two versions of the single-step task. In the within version of the task, the representation of the flashed stimulus remained within a single hemifield (Fig. 1B). In the across version of the task, the representation of the flashed stimulus shifted across hemifields (Fig. 1A). Heiser and colleagues found that neurons in LIP are capable of remapping both within and across hemi-
The differences between the layers suggest that the activity in the intermediate layers of the SC must be influenced by activity in cortex, whereas activity in the superficial layers need not be. Activity in the SC that originates independent of cortex may be the source of the preserved remapping in area LIP in the split brain monkeys.

**Methods**

### General procedures

Four rhesus macaques (*Macaca mulatta*, 5–9 kg) were used in this study. The forebrain commissures of monkeys EM and CH were surgically transected (Berman et al. 2005, 2007; Heiser et al. 2005). In the control animals FF and OP, the forebrain commissures remained intact. Animals were cared for and handled in accordance with National Institutes of Health guidelines, and all experimental protocols were approved by the University of Pittsburgh Institutional Animal Care and Use Committee.

The commissurotomy is described in detail elsewhere (Berman et al. 2005; Vogels et al. 1994). Briefly, the monkeys were prepared for surgery with dexamethasone, and anesthesia was induced with ketamine and maintained with isoflurane. Mannitol was administered throughout the surgery to minimize tissue swelling. The corpus callosum was transected along its full length using a small glass pipette with suction; the anterior commissure was fully transected. In the 2 wk after the surgery, analgesics and antibiotics were administered daily.

All four monkeys underwent sterile surgery to implant an acrylic cap with an embedded head restraint bar, scleral search coils, and a recording chamber. General anesthesia was induced with ketamine and was maintained with isoflurane. The acrylic cap was secured with embedded screws inserted into the skull. The recording chamber was positioned on the midline, angled posteriorly at ≈40°. The SC was ≈25–30 mm below the surface of the brain. The SC was identified by a large burst of neuronal activity in response to visual stimuli. This signaled the entry of the electrode into the surface of the SC. As the electrode moved from the superficial layers to the intermediate layers, neurons fired not only for visual stimuli but also around the time of a saccade. We used MRI to guide and verify correct placement of the chambers.

### Physiological methods

During recording sessions, the monkey sat in a darkened room with its head fixed in a primate chair facing a tangent screen. Visual stimuli were back-projected on the tangent screen using a LCD projector. Stimulus presentation was under the control of two computers running a C-based program, CORTEX, made available by Dr. Robert Desimone. Eye position was monitored using scleral search coils (Judge et al. 1980) with a sampling rate of 250 Hz.

Neural activity was recorded using tungsten microelectrodes (Frederick Haer, Bowdoinham, ME) inserted into SC through stainless steel guide tubes that were stabilized in a nylon grid system (Crist Instruments). The neural signal was amplified and filtered with a band-pass of 500 Hz to 5 kHz. Individual neurons were isolated with an on-line spike-sorting system using a template-matching algorithm (Signal Processing Systems, Prospect, Australia) or with both on- and off-line template matching and principle component analysis (Plexon, Dallas, TX).

### Behavioral paradigms

**SINGLE-STEP TASK.** The trial began with the monkey fixating a central fixation point for 300–500 ms. A visual stimulus appeared in the periphery at the same time as a target for a visually guided
saccade. The visual stimulus was turned off after 50 ms at the same time as the fixation point. Extinction of the fixation point was the cue to the monkey to make a saccade to the illuminated target. The saccade target was positioned so that the RF of the neuron landed on the screen location where the visual stimulus had been flashed. The monkey fixated the new target for 500–700 ms to receive a liquid reward.

DOUBLE-STEP TASK. The arrangement of the stimuli for the double-step task was identical to the arrangement used for the single-step task. The major difference between the tasks is that the monkey made a second saccade to the flashed stimulus in the double-step task. The monkey began by fixating a central point for 300–500 ms. The target for the first saccade (T1) was turned on and remained on. The second target (T2) appeared 100 ms later and remained on for 50 ms. The T2 target was at the same spatial location as the flashed stimulus in the single-step task. The FP was turned off simultaneously with the disappearance of T2. This cued the monkey to make two saccades: a visually guided saccade to T1 and then a second, memory-guided saccade to T2. The T1 target was turned off at the completion of the first saccade. Once the monkey reached the T2 location, the T2 target reappeared to provide feedback on the correct target locations. The monkey maintained fixation at the T2 location for 300–500 ms and then received a liquid reward.

STIMULUS ONLY CONTROL TASK. The stimulus only control task was used to ensure that the stimulus location was outside the RF of the neuron. The monkey fixated for 300–500 ms, and then a visual stimulus was flashed for 50 ms in the same location as in the single-step task. In contrast to the single-step task, no saccade was made; the monkey fixated for an additional 1,200–1,500 ms before a reward was received. Only neurons that showed no significant activity (t-test, \( P < 0.05 \)) in the visual epoch (50–250 ms after stimulus onset) as compared with the baseline epoch (200–300 ms after start of fixation) were included for further analysis.

SACCADE ONLY CONTROL TASK. The saccade only control task was used to determine the extent to which activity observed in the single-step task was due to the eye movement. The configuration and timing of the task differed from the single-step task in only one respect; the peripheral visual stimulus was not displayed. Many cells had significant activity during the saccade only control task. It is possible that the activity observed in the saccade only task was due to the eye movement. This is unlikely because the eye movement was always made to a target outside the receptive field of the neuron. Another possibility is that the activity was due to remapping of the fixation point (Heiser and Colby 2006). Remapping of the fixation point occurs if the receptive field of the neuron lands on the screen location where the fixation point had been presented. To take this activity into account, we subtract the activity measured during the saccade only task from the activity measured in the single-step task.

MEMORY-GUIDED SACCADE TASK. In the memory-guided saccade task (MGS), the monkey began the trial by fixating for 300–500 ms. Next, a stimulus was flashed inside the RF of the neuron for 50 ms. The monkey maintained fixation during the stimulus presentation and for an additional 400–800 ms. Finally, the fixation point was turned off and the monkey made an eye movement to the remembered stimulus location. After the saccade, the visual stimulus reappeared and the monkey maintained fixation at the cued location for an additional 300–500 ms.

### Experimental design

We started each recording session with the MGS task to determine the location of the neuron’s RF and to classify the neuron. We determined the RF location by flashing the stimulus at ≤24 standard locations. If the neuron responded to more than one location, we manually adjusted the stimulus location to find the optimal location. A neuron was classified as being in the superficial layers of the SC based on the recording location and the response of the cell. We classified a neuron as superficial if it was recorded within 600 \( \mu \)m of the surface of the SC. Additionally, it was classified as a superficial neuron if it had a visual response (50–150 ms after stimulus onset) and no response during the delay period (−200 to −100 from saccade onset) or around the time of the saccade (−30 to 30 from saccade onset). Neurons below 600 \( \mu \)m were classified as intermediate. We further divided the intermediate layer neurons into seven classes based on their responses during the visual, delay, and saccade epochs (Table 1).

Our criteria were similar to those used previously (Goldberg and Wurtz 1972; Marrocco and Li 1977; Mayo and Sommer 2008; McPeek and Keller 2002; Richmond and Wurtz 1980; Wurtz and Mohler 1976). Another standard method of classification is to divide SC neurons as either build-up or burst neurons (Basso and Wurtz 1998; Munoz and Wurtz 1995). We chose to classify types of cells based on the epoch of activity to directly compare them to cortical area LIP.

Once we determined the RF of the neuron, we collected data during five tasks. There were two conditions for each task (within and across) for a total of 10 trial types. The tasks were run in separate blocks, always in the same order: stimulus only control, saccade only control, single-step, double-step, and MGS from T1 location to T2 location. We collected the data in this order because intertrial memory responses can persist after experience with a remapping task (Umeno and Goldberg 2001). In each block, the within-hemifield and across-hemifield conditions were randomly interleaved. We collected 12–20 trials of each trial type.

The exact geometry of the within-hemifield and across-hemifield conditions was tailored for each neuron based on the location of the RF (Fig. 1). By definition, different spatial configurations were required for remapping stimulus traces within and across hemifields. We held saccade amplitude constant and varied only the direction of the first saccade to achieve the within and across conditions. The second saccade always had the same direction and amplitude for the two conditions because it was described by the vector between central fixation and the neuron’s RF. We used two standard configurations for most neurons. In the within-hemifield condition, a vertical saccade...

### Table 1. Classification of cell type

<table>
<thead>
<tr>
<th></th>
<th>Split-Brain</th>
<th>Intact</th>
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<tbody>
<tr>
<td></td>
<td>Within Only</td>
<td>Across Only</td>
</tr>
<tr>
<td>Vis</td>
<td>11 (44)</td>
<td>4 (16)</td>
</tr>
<tr>
<td>Vis-Delay</td>
<td>2 (40)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Vis-Sac</td>
<td>3 (21)</td>
<td>5 (36)</td>
</tr>
<tr>
<td>Vis-Delay-Sac</td>
<td>2 (50)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Delay-Sac</td>
<td>2 (67)</td>
<td>0 (0)</td>
</tr>
<tr>
<td>Sac</td>
<td>0 (0)</td>
<td>2 (67)</td>
</tr>
<tr>
<td>Delay</td>
<td>2 (67)</td>
<td>0 (0)</td>
</tr>
</tbody>
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Parentheses enclose percentages.
kept the representation of the second target within the same hemifield both before and after the first saccade. In the across-hemifield condition, a horizontal ipsiversive saccade moved the representation of T2 from one hemifield to the other. For some neurons, due to the location of the RF, it was necessary to use a diagonal first saccade for one or both conditions.

**Data analysis**

**MEASURING REMAPPING ACTIVITY FOR THE SINGLE-STEP TASK.** We measured activity in identical epochs for the single-step and saccade only control tasks (0–300 ms from saccade onset). Remapping activity was defined as the activity in the single-step task that exceeded activity in the corresponding saccade control task. A neuron was considered to have significant remapping activity if the activity during the single-step task was significantly greater than activity during the saccade control task (1-sided t-test \( P > 0.05 \)). We used a simple subtraction to quantify the remapping response: remapping = single-step activity − saccade control activity.

**WITHIN-ACROSS INDEX.** We computed a within-across index to quantify the strength of remapping activity for the within condition compared with that in the across condition: WA index = \((SSw - SACw) - (Ssa - SACAa)/(SSw + SACw) + (Ssa + SACAa)\).

The index normalized remapping activity from the single-step task to the total activity in the single-step and saccade control tasks. SSw and SSA represent the average activity in the single-step task in the within and across conditions, respectively. SACw and SACAa represent the average activity in the corresponding saccade control conditions. The denominator of this formula accounted for the fact that the saccade-alone activity exceeds the single-step activity for at least one condition in some neurons.

**MEASURING NEURAL LATENCY FOR SINGLE-STEP TASK.** We defined the neural latency of remapping activity as the time when the response in the single-step task first became significantly different from the activity in the saccade control task. We searched for the beginning of activity in an epoch from 150 ms before to 250 ms after the onset of the saccade. We used a 20 ms bin at corresponding time intervals in the single step and saccade only tasks. We compared the activity in the corresponding bins using a one-sided t-test \( (P < 0.05) \). We then shifted the bin 5 ms forward and repeated the procedure. We defined the neural latency as the middle of the first of three consecutive bins that were significantly different between the two tasks.

**ROC ANALYSIS.** We determined the time course of selectivity for within compared with across hemifield remapping activity by performing a sliding receiver operating characteristic (ROC) analysis (Johnston et al. 2009). We performed an ROC analysis for each neuron in successive bins of 50 ms shifted by 10 ms. We performed this calculation on responses 200 ms before to 400 ms after the onset of the saccade. For each time bin, we determined the ROC value or the area under the curve. The ROC values were averaged for all neurons. An ROC value of 0.5 indicates no difference in the magnitude of response between conditions. A value \( >0.5 \) indicates greater activity for within conditions; a value \( <0.5 \) indicates greater activity for across conditions. To determine the likelihood that the ROC value was significantly greater than chance, we performed a bootstrap analysis. For each neuron, we randomly determined if the assigned condition (within or across) would remain unchanged or if the condition would be reversed. If the conditions were reversed, we re-calculated the ROC values, using firing rates of across trials as within trials and vice versa. We then averaged ROC values for all neurons, regardless of whether the conditions changed or remained the same. We repeated this procedure 10,000 times. From the distribution of 10,000 averaged ROC values we determined the 95th and 5th percentiles. Nonrandomized ROC values were considered significant if they were above the 95th percentile or below the 5th percentile.

**TRIAL-BY-TRIAL ANALYSIS.** Our assessment of the relationship between neurons and behavior included an analysis of the trial-by-trial correlation between updating activity in single neurons and double-step saccade performance. We used the following method to remove the contributions of saccade-alone firing from double-step activity on single trials. For a given neuron, we computed the double-step firing rate for each trial measuring the spikes per second in the epoch from the beginning of the first saccade to the beginning of the second saccade. From each individual-trial double-step firing rate, we then subtracted the average saccade-alone firing rate for that condition (within or across). The average saccade-alone firing rate was computed using the epoch corresponding to the average double-step epoch for that neuron and condition. This method allowed us to remove the contributions of saccade-alone activity while maintaining information about updating activity on individual trials. We assessed the relationship between updating activity and behavior (accuracy or latency) by performing a Pearson’s correlation analysis.

**RESULTS**

We characterized activity in the SC and related it to spatial behavior. We recorded from 246 neurons in two split brain monkeys and compared them to 173 SC neurons recorded from two intact animals. We excluded neurons if they had significant activity during the stimulus control task. For the split brain monkeys, we recorded 118 intermediate layers cells and 72 superficial layers cells. For the intact monkeys, we recorded 75 intermediate layers cells and 45 superficial layers cells.

**SC neurons remap stimulus traces across hemifields in split brain monkeys**

Our primary finding is that individual neurons in the SC can remap visual information both within- and across-hemifields after the forebrain commissures are transected. An example neuron is shown in Fig. 2. This cell was recorded from the intermediate layers of the SC. In the memory-guided saccade task, the cell had a strong visual response to a stimulus that was presented inside the RF (Fig. 2K) as well as delay period and saccade related activity (L). During the within condition of the single-step task, the neuron fired at the time of the saccade and activity continued for several hundred milliseconds (Fig. 2C). Two control conditions showed that this activity was not due to either the stimulus or the saccade alone. First, there was no response in the stimulus only control in which the visual stimulus was presented outside the RF and no eye movement was made (Fig. 2E). Second, there was no significant response in the saccade only control in which the saccade was made without the peripheral stimulus having been presented (Fig. 2G). The critical question was whether this same neuron would respond when information had to be transferred across hemifields. This cell was active in the across condition of the single-step task. This activity indicates that the memory trace of the stimulus was remapped in conjuction with the saccade (Fig. 2D). There was no significant activity in either of the across control conditions (Fig. 2, F and H). In the absence of the forebrain commissures, this SC neuron remapped visual information both within and across hemifields.

In the superficial layers of the SC, we also found neurons with remapping activity during both the within and across conditions of the single-step task. An example of a cell re-
REMAPING ACTIVITY IN THE SC OF THE SPLIT BRAIN MONKEY


corded from the superficial layers of the SC is shown in Fig. 3. In the memory-guided saccade task, the cell fired strongly to the stimulus and saccade control conditions (Fig. 3, E and G). The cell fired during the across condition of the single step task (Fig. 3D). There was also a small response during the across condition of the saccade control task (Fig. 3H). However, the responses in the two conditions are significantly different (t-test, \( P < 0.05 \)). In the superficial layers, as in the intermediate layers, neurons can remap across hemifields even in the absence of the forebrain commissures.

More neurons in the intermediate layers remap for within compared with across hemifields

We asked whether across-hemifield remapping was comparable to within-hemifield remapping in the intermediate layers of the SC of the split brain monkey at a population level. We found that 48% (57/118) of cells in the intermediate layers had significant remapping activity in at least one of the remapping conditions (Fig. 4C). Of these cells, most had significant activity either in both conditions (42%, 24/57, Fig. 4C, blue dots) or in the within condition only (39%, 22/57, C, green dots). Fewer cells had significant activity in only the across-hemifield remapping condition (19%, 11/57, Fig. 4C, red dots). In the intact animal, just over 50% (38/75) of cells remap in at least one of the conditions. Similar proportions of cells had significant remapping activity in the within only (31.5%, 12/38, Fig. 4D, green dots), across only (31.5%, 12/38, D, red dots), and both conditions (36%, 14/38: D, blue dots). The distributions of the proportion of neurons with remapping activity are significantly different for split brain compared with intact animals (\( \chi^2 = 7.09, df = 2, P < 0.05 \)). We conclude that the reduced prevalence of across-hemifield only remapping in the intermediate layers of the SC resulted from the removal of the forebrain commissures.

We compared the results from the intermediate layers of the SC to our previous results in area LIP (Heiser and Colby 2006; Heiser et al. 2005). In area LIP, we found a substantial reduction in remapping for the across-hemifield condition in the split brain monkeys (see supplementary material1). The findings in LIP and intermediate SC are not identical. While both regions showed a decrease in the number of neurons with remapping activity in the across-only condition, the decrease was much more pronounced in area LIP. Area LIP and intermediate SC are also different if we classify neurons by response type. For area LIP, there were across only reductions in all four classification types (Vis, Vis-Delay, Vis-Sac, Vis-Delay-Sac) (Heiser et al. 2005). For the intermediate SC, within-hemifield remapping was more common than across-hemifield remapping for five of the seven classification types (see Table 1). We had more classification types in the SC because we did not restrict our study to neurons with activity during the visual epoch as we did for area LIP. The major difference between area LIP and the intermediate SC is for Vis-Sac neurons. In the intermediate SC, we found that across only remapping was more common than within only. While we found a decrease in the number of cells with across-hemifield remapping in both area LIP and the intermediate SC, the overall percent decrease, and type of neurons that had a decrease, differed between the two areas.

1 The online version of this article contains supplemental data.
Neurons in the superficial layers of the SC showed a different pattern of results than either the intermediate layers of the SC or area LIP. We found that 37% (27/73) of neurons remap in the superficial layers in the split brain monkeys. Of those that remap, fewer than half had significant remapping activity in the within only (26%, 7/27, green dots), across only (30%, 8/27, red dots), and both (44%, 12/27, blue dots) conditions. In the intact monkey, 38% of neurons (17/45) remapped overall. Of those, 35% (6/17, green dots) remapped in the within only, 35% (6/17, red dots) in the across only, and 30% (5/17, blue dots) in both conditions. There is a significant difference between intact and split brain animals ($\chi^2, P < 0.001$). There are more neurons in the split brain monkeys that remap for both conditions, but there are equivalent proportions of neurons that remap for within and across only. This pattern is significantly different from both area LIP and the intermediate SC (superficial vs. intermediate, $\chi^2 = 8.97$, df = 2, $P = 0.01$; superficial vs. LIP, $\chi^2 = 47.95$, df = 2, $P < 0.001$). We conclude that the absence of the forebrain commissures does not influence the proportion of cells that remap across hemifields in the superficial layers of the SC.

Strength of across-hemifield remapping is attenuated in the intermediate layers of the SC in split brain monkeys

In the intermediate layers of the split brain monkeys, fewer neurons overall remap across hemifield compared with within hemifield. We asked whether those that did remap across hemifield did so with equal strength as those that remapped within hemifield. We found that the magnitude of across hemifield remapping was reduced compared with within hemifield (Wilcoxon matched-pairs test, $P = 0.02$; Fig. 4C). We restricted this and all subsequent analyses to cells that had significant remapping for at least one of the conditions. In the intact monkey, there was no difference in magnitude for within and across-hemifield remapping in the intermediate layers (Wilcoxon matched-pairs test, $P > 0.05$; Fig. 4D). The present results in intermediate SC are similar to our previous results in LIP. In LIP, we found that the magnitude of across-hemifield remapping was significantly reduced compared with within-hemifield remapping in the split brain monkeys (see supplementary materials).

The reduced magnitude of remapped responses for across conditions was found both in the intermediate layers of the SC and area LIP. In contrast, in the superficial layers, there was no...
no fundamental differences between activity during the within and across saccade only conditions, the WA index reflects only differences for within and across remapping.

We found stronger remapping for within-hemifield trials in the intermediate layers of the SC in the split brain monkeys. The distribution of WA index values from the intermediate layers of the SC of the split brain monkeys was significantly shifted toward positive values (sign test, $P = 0.02$; Fig. 5C), indicating stronger remapping for the within-hemifield condition. In contrast, in the intact animals, the distribution of WA index values was centered near zero (sign test, $P = 0.51$; Fig. 5D). When we compared the split brain animals to the intact animals, we found a significant difference between the two populations (Wilcoxon rank sum, $P = 0.02$). The magnitude of across-hemifield remapping was reduced in the intermediate layers of the SC in the absence of the forebrain commissures. These results mirror our findings from area LIP in split brain and intact monkeys (see supplementary materials). In the absence of the forebrain commissures, the across-hemifield remapping signal is reduced in both the intermediate layers of the SC and in area LIP.

We found a different result in the superficial layers of the SC of the split brain animals compared with that found in the intermediate layers of the SC and in LIP. In the superficial layers, we found no significant shift in the WA index distributions for either split brain or intact monkeys (sign test, $P > 0.05$, Fig. 5A). These results reveal a distinction between remapping activity observed in the superficial layers of the SC compared with both area LIP and to the intermediate layers of the SC (Wilcoxon rank sum, $P < 0.05$). There is no reduction in across-hemifield remapping in the superficial layers, whereas there is in the intermediate layers and area LIP.

A potential problem could arise with this index if there were fundamental differences between activity in the saccade only conditions for within and across. If this was the case, then the WA index would reflect differences in saccade only activity, not just differences in remapping activity. We found no differences in average firing rate for within and across conditions during the saccade only task. This was true for both superficial and intermediate layers of the SC in the split brain and intact monkeys (Wilcoxon matched-paired test, superficial split brain: $P = 0.62$, superficial intact: $P = 0.76$, intermediate split brain: $P = 0.69$, intermediate intact: $P = 0.30$). Given that there are
The results on the strength of remapping are summarized in Table 2. In our previous study, we found that split brain monkeys were impaired on performance in the double-step task, a behavioral task that depends on accurate spatial updating (Berman et al. 2005). This behavioral impairment corresponded to a reduction in neural activity. Across-hemifield remapping activity was reduced compared with within-hemifield remapping in area LIP. In the current study, we found that the intermediate layers of the SC resembled area LIP; across-hemifield remapping was reduced compared with within-hemifield remapping. In contrast, there was no reduction of across-hemifield remapping in the superficial layers of the SC.

Earliest across-hemifield remapping signals are absent in the intermediate layers of the SC of the split brain monkeys

There was considerable variability in the latency of remapping in all brain regions in both intact and split brain animals. This is consistent with previous studies in which a wide range of latencies have been observed (Duhamel et al. 1992; Goldberg and Bruce 1990; Heiser and Colby 2006; Nakamura and Colby 2002; Sommer and Wurtz 2006; Umeno and Goldberg 1997; Walker et al. 1995). The variability in latency could be due to a single mechanism that occurs at different times, or multiple mechanisms that each has its own time course (Goossens and Van Opstal 1997; Vliegen et al. 2005; Wang et al. 2007).

Remapping is considered predictive if the response in the single-step task (relative to the beginning of the saccade) occurs earlier than the visual latency observed in the memory-guided saccade task. These predictive signals provide an updated representation well before reafferent visual signals are available. We asked whether the occurrence of a predictive signal in the intermediate layers of the SC is dependent on the forebrain commissures.

We analyzed the entire population of neurons for which a latency could be determined. We found a similar proportion of predictive responses for within- and across-hemifield remapping in neurons in the split brain monkeys (Fig. 6C, ■, within 66%, across 63%, \( \chi^2 \) with Yates correction, df = 1, \( P = 0.95 \)). In contrast, in the intact monkeys, we found more neurons with across-hemifield predictive remapping than neurons with within-hemifield predictive remapping (Fig. 6D, ■, within 48%, across 77%, \( \chi^2 \) with Yates correction, df = 1, \( P < 0.05 \)). In the superficial layers of the SC in the split brain and intact monkeys, there were equivalent proportions of neurons that had predictive responses for within and across-hemifield remapping. For the split brain monkeys, 56% of neurons predictedly remap within-hemifield and 53% for across (Fig. 6A, ■, \( \chi^2 \) with Yates correction, df = 1, \( P = 0.95 \)). In the intact monkey, 57% predictively remapped for within and 50% for across (Fig. 6B, ■, \( \chi^2 \) with Yates correction, df = 1, \( P = 0.98 \)).

We conclude that the occurrence of predictive remapping across-hemifield does not depend on the forebrain commissures for either the intermediate or the superficial layers of the SC.

For a subset of predictive neurons, the response in the single-step task begins even before the onset of the saccade. For remapping to occur before the eye moves, information about the upcoming saccade must be available. A copy of the eye movement command, or a corollary discharge signal, must be involved when remapping is presaccadic.

We asked whether presaccadic remapping was selectively reduced in split brain monkeys. We reasoned that remapping that occurs before the saccade requires a corollary discharge signal, while remapping that occurs later may not. In contrast to our findings on the overall number of predictive neurons, we found that presaccadic responses were more common for within-hemifield remapping than for across in the intermediate layers of the SC in the split brain monkeys (Fig. 6C, ■, within 49%, across 24%, \( \chi^2 \) with Yates correction, df = 1, \( P < 0.05 \)). In the intact monkey, presaccadic latencies occurred with greater frequency for the across condition than within condition (Fig. 6D, ■, within 38%, across 40%, \( \chi^2 \) with Yates correction, df = 1, \( P = 0.95 \)). The results for presaccadic remapping in the intermediate layers of the SC in the split brain monkey are similar to those previously observed in area LIP.

### Table 2. Across-hemifield remapping compared to within-hemifield remapping

<table>
<thead>
<tr>
<th>Behavior</th>
<th>Split-Brain</th>
<th>Intact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnitude of response</td>
<td>Impaired, then recovers</td>
<td>Same</td>
</tr>
<tr>
<td>Superficial SC</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Intermediate SC</td>
<td>Reduced</td>
<td>Same</td>
</tr>
<tr>
<td>LIP</td>
<td>Reduced</td>
<td>Same</td>
</tr>
<tr>
<td>Latency of response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superficial SC</td>
<td>Same</td>
<td>Same</td>
</tr>
<tr>
<td>Intermediate SC</td>
<td>Delayed</td>
<td>Same</td>
</tr>
<tr>
<td>LIP</td>
<td>Delayed</td>
<td>Same</td>
</tr>
</tbody>
</table>

SC, superior colliculus; LIP, lateral intraparietal cortex.

**FIG. 6.** Proportion of neurons with significant predictive and presaccadic remapping for within- and across-hemifield conditions. Predictive neurons began their remapping response before the visual latency of the neuron in the memory-guided saccade task. Presaccadic neurons are the subset of predictive neurons in which remapping is observed before saccade onset. A and B: in the superficial layers of the SC, an equal proportion of neurons show significant predictive (■) and presaccadic (□) remapping for within and across conditions. C: in the intermediate layers of split brain monkeys, a lower proportion of neurons show significant presaccadic remapping for across versus within conditions. D: in the intermediate layers of the intact monkey, more neurons have predictive and presaccadic remapping for across conditions.
We concluded that in the intact animal there is no difference in the timing of remapping when information remains within or must be transferred across hemifields. This result is true for both the SC and area LIP in the intact animal. In the absence of the forebrain commissures, however, the remapped response is delayed when information must be transferred across hemifields. This is the case for both LIP and the intermediate layers of the SC. These results are summarized in Table 2.

**Time course of across-hemifield remapping is altered in the intermediate layers of the split brain monkeys**

We analyzed the time course of signals during within- and across-hemifield remapping. We calculated the ROC value over time for the population of neurons that showed significant remapping for both within and across conditions (Fig. 8). The ROC values were computed for each neuron in a 50 ms epoch that was successively shifted by 10 ms. We averaged the ROC values for all neurons in each group and determined the point at which the values became significant using a bootstrap method. A ROC value of 0.5 indicates no difference between within- and across-hemifield remapping. The activity was defined as significantly greater for within-hemifield remapping when the average ROC value was greater than the 95th percentile determined by the bootstrap analyses.

**Neurons in the intermediate layers of the SC remap earlier within hemifield than across hemifield**

Across the population, more neurons have presaccadic remapping during within-hemifield conditions in the intermediate layers of the SC in the split brain monkeys. Is this the case at the single neuron level? We directly compared neural latency for within and across remapping in individual neurons (Fig. 7). By definition, this analysis included only neurons for which valid latencies could be determined in both conditions. Points that fall along the unity line represent neurons with remapping activity that began at the same time for the within and across conditions. For the intermediate layers of the SC in intact animals, remapping latency is equal for within and across conditions. For the intermediate layers of the SC in the split brain monkeys, remapping during across conditions occurs later than remapping during within conditions. B: in the intact animal, remapping latency is equal for within and across conditions.

When the forebrain commissures are removed, remapping that occurs before the saccade is selectively reduced for across-hemifield conditions for area LIP and the intermediate layers of the SC.

In contrast, in the superficial layers of the SC in the split brain monkey, we found an equivalent number of neurons with presaccadic remapping for within-hemifield (43%) and across-hemifield (32%, Fig. 6A, with Yates correction, df = 1, P = 0.63). Likewise in the intact animals, we found similar proportions with presaccadic remapping for within-hemifield (50%) and across-hemifield (33%, Fig. 6B, with Yates correction, df = 1, P = 0.98). The results observed in the superficial layers of the SC cannot be due to the absence of the forebrain commissures. The different pattern of results for presaccadic remapping in the superficial layers compared with intermediate layers of the SC suggests that the source of remapping is different for neurons in these layers.

We concluded that in the intact animal there is no difference in the timing of remapping when information remains within or must be transferred across hemifields. This result is true for both the SC and area LIP in the intact animal. In the absence of the forebrain commissures, however, the remapped response is delayed when information must be transferred across hemifields. This is the case for both LIP and the intermediate layers of the SC. These results are summarized in Table 2.
Around the time of the saccade, the remapped signal in the SC decreases significantly. Remapping activity declines drastically because the monkey is making an eye movement to a target outside of the neuron’s receptive field. When the firing rate is extremely low, a few spikes can make a large difference in the ROC measurement. This suppression of activity makes the measurement unreliable around the time of the saccade. To avoid this unreliability, we omitted the ROC values in an epoch 50 ms after the saccade.

In the absence of the forebrain commissures, the ROC value for the intermediate layers of the SC first became significant 90 ms before the onset of the saccade (Fig. 8C). The data show that, well before the initiation of the saccade, there is a difference in the neural signal associated with updating stimulus traces for within compared with across-hemifield conditions. This difference persists for hundreds of milliseconds after the saccade is completed. In contrast, in the intact animal, the ROC value never exceeds the 95th percentile throughout the duration of the analysis epoch (Fig. 8D). There are some time points where the data are below the 5th percentile; however, overall remapping is not stronger for within compared with across. The results for the intermediate layers of the SC are consistent with our previous time course analysis in area LIP (Heiser et al. 2005). There was greater within compared with across-hemifield remapping activity before and after the saccade only in the split brain monkeys in both SC and LIP.

The time course of the ROC value in the superficial layers of the SC differed from the time course for the intermediate layers and area LIP. For the superficial layers in the split brain animals, the ROC value, for the most part, does not exceed the values determined by the bootstrap method (Fig. 8A). Similarly in the intact animals, the majority of the ROC values are not significantly different from chance (Fig. 8B). There are a few time points before the saccade that are above the 95th percentile. At approximately the same time points, ROC values are approaching significance in the split brain animals. Unlike the results observed in the intermediate layers, the difference in magnitude between the within and across conditions was not due to the absence of the forebrain commissures. The difference in results between the intermediate and superficial layers further supports the idea that the source of remapping differs between layers.

**Performance on the double-step task**

In our previous study, performance on the across-hemifield version of the double-step task was initially impaired in the split brain monkeys (Berman et al. 2005). With experience on a standard sequence of targets, the monkeys’ performance markedly improved. Nonetheless there was still a difference in accuracy for within compared with across sequences 4 yr post surgery. In the present study, we asked if we could still, at almost 6 yr, detect a difference in performance on within and across conditions of the double-step task in the split brain monkeys.

We quantified the accuracy of the monkey’s performance on the double-step task by computing the distance error of the second saccade. For each trial, we measured the distance between the second target location and the endpoint of the second saccade. We included only trials in which the eye accurately reached the first target. We computed the distance error for all recording sessions and found that on average the error of the second saccade was significantly greater for the across than for the within conditions (Fig. 9A). Even with the experience gained both during the original behavioral tests and during subsequent LIP recording sessions, the split brain monkeys were still impaired on across-hemifield sequences of the double-step task. We found no significant difference between distance error in within and across conditions in the intact monkey (Fig. 9B).

We also quantified performance by measuring the saccade latencies of the first and second saccades. We asked whether there was a difference in saccade latencies for the within and across conditions of the double-step task. We found that the split brain monkeys had slower first and second saccades for the across-hemifield condition compared with the within-hemi-
field condition (Fig. 9, C and E). For the first saccade, the average latency was 121 ± 25 (SD) ms for the within conditions compared with 141 ± 52 ms for across. For the second saccade, the average latency was 139 ± 46 ms for the within conditions compared with 141 ± 52 for the across conditions. In addition to making more errors, the split brain animals took longer to complete the across-hemifield condition of the double-step task. We found no difference in either the first or second saccade latencies for the intact monkey for within compared with across conditions.

We compared the results of the saccade latency analysis from the SC recording sessions to the results of the same analysis from the LIP recording sessions. We expected that after 4 yr performance would stabilize, but this was not the case. During the LIP recording sessions, on average, the split brain monkeys were faster for the second saccade for the across conditions than for the within conditions (Berman et al. 2007). These results from the LIP recording sessions stand in contrast to our current results in the SC recording sessions.

In summary, we found a difference in performance on the double-step task for the within and across conditions in the split brain monkeys during SC recording sessions. We found that the monkeys were faster and more accurate for within-hemifield sequences compared with across-hemifields sequences of the double-step task. Even after years of recovery, the absence of the forebrain commissures still influences the behavior of the monkey.

Remapping activity in the intermediate layers of the SC is related to behavior on the double-step task

Is the magnitude of remapping activity in the intermediate layers of SC related to accuracy of performance on the double-step task? We know from the preceding analyses that there are differences in the relationship between remapping activity and performance for within and across conditions in the split brain monkeys (Figs. 4 and 9). We asked if a relationship between activity and behavior could be detected on a trial-by-trial basis. We wanted to know whether, on a given trial, performance was more accurate when remapping activity was stronger. We addressed this by calculating the Pearson’s correlation coefficient (r) for the relationship between the distance error and remapping activity for each neuron. If remapping activity for the population of intermediate SC neurons were related to performance, then the distribution of r values would be shifted away from zero.

We did the trial-by-trial analysis in two ways. We first computed the r value using a combination of trials from both the within and across conditions. The combined trial-by-trial analysis measured differences in neural activity and behavior that could be observed in a single neuron between within and across conditions. In the second analysis, we computed the r value separately for the within and across conditions. This separated trial-by-trial analysis allowed us to detect a relationship between activity and behavior that is not simply due to overall differences between within and across remapping.

In the following sections, we compare neuronal activity to the accuracy of the second saccade during the double-step task. We perform two trial-by-trial analyses for the intermediate layers of the SC, area LIP, and the superficial layers of the SC. As a control, we compare neuronal activity to accuracy during a memory-guided saccade task. Finally, we use the same analyses to compare neuronal activity to the saccade latency.

FOR ALL TRIALS COMBINED, DOUBLE-STEP NEURONAL ACTIVITY IS NOT RELATED TO BEHAVIORAL ACCURACY. In our first analysis of the relation between behavioral performance and neuronal activity, we combined trials from within and across conditions of the double-step task. In the split brain monkeys, we found that there was a trend for the distribution of r values to be shifted negatively in the intermediate layers of the SC. The shift, however, was not significant (Fig. 10A, mean r = -0.12, P = 0.06, sign test). A negative shift means that there was on average a negative correlation between neural activity on a given trial and the distance error on that trial. When the firing rate was higher, the distance error was lower, i.e., the saccade was more accurate. In the intact animal, we found no shift in the distribution of r values (Fig. 10B, mean r = -0.003, P = 0.58, sign test). An equal number of cells had positive and negative r values.

FIG. 10. Trial-by-trial analysis for intermediate layers: relationship between remapping activity and S2 distance error. Panels show the distribution of r values for the trial-by-trial correlation between remapping activity of intermediate layer SC neurons and S2 error. Vertical lines indicate r = 0. Note that only for split brain monkeys during across-hemifield trials (E) is the distribution of r values significantly shifted from 0. Negative r values indicate that greater remapping activity led to lower S2 error, whereas positive values indicate the opposite. Top: data for all trials. Middle: within-hemifield trials only. Bottom: across-hemifield trials only.
The trend observed in the intermediate layers of the SC was more pronounced in previous results obtained from LIP (see supplementary material). We found in LIP that there was a small but significant relationship between firing rate and the performance of the monkey on the double-step task. However, this result could also reflect differences between the within and across conditions already observed. If there were a true relationship between activity in area LIP and performance, then we would expect to see this relationship independent of the conditional differences (within vs. across trials). We therefore carried out a second analysis where differences between conditions would not be a factor.

**For across trials only, double-step neuronal activity is related to behavioral accuracy.** In the second analysis, we separated the within and across trials. We calculated a separate correlation coefficient for each trial type. If there was a true relationship between firing rate and performance, then we should have observed a significant shift in the r distributions for each condition. We found no significant relationship between remapping activity in LIP and accuracy of the performance when the conditions were analyzed separately (see supplementary materials). In other words, once the conditional differences were removed, there was no relationship. We also found no relationship between firing rate and performance on a trial-by-trial basis in the intact animal. This was true for both the combined and separated data sets. One reason for the absence of a significant result in the intact monkey could be the lack of variability in accuracy. When the monkey is performing the task correctly, there is very little variability in performance. It is only with greater variability, as is the case for the split brain monkeys, that a relationship can be detected.

We also carried out this second analysis for the intermediate layers of the SC. While we found no relationship between firing rate and accuracy for the within trials, we did find a relationship for the across trials. The r distribution for the across trials was significantly shifted toward the negative (Fig. 10E, mean r = −0.17, P < 0.0001, sign test). On a trial-by-trial basis, if the firing rate was higher, the monkey was more accurate. This relationship was not present in the intact monkey (Fig. 10F, mean r = −0.03, P = 0.57, sign test). In sum, when the forebrain commissures are transected, a higher firing rate in the intermediate layers of the SC is correlated with improved performance for across-hemifield trials.

**Memory-guided saccade neuronal activity was not related to behavioral accuracy**

Before we can conclude that there is a relationship between remapping activity in the SC and the behavior of the monkey, we must consider an alternative explanation. The SC is known for its role in saccadic eye movements. Most SC neurons fire when a saccade is made into the receptive field. The second saccade of the double-step task is, by design, always into the receptive field of the neuron. It is thus possible that some of the activity measured in the double-step task was due to the eye movement and not due to remapping. To test this possibility, we added a new control task in which the monkey made a memory-guided saccade into the receptive field (see METHODS). Orbital position effects were an additional concern. It is known that the position of the eye in the orbit can modulate neuronal activity in many brain areas, including the SC (Campos et al. 2006; Van Opstal et al. 1995). To eliminate potential orbital position effects, we matched the memory guided saccade task configuration to the double-step configuration. During this memory-guided saccade task, the monkey initially fixated at the double-step T1 location. The stimulus was flashed at the double-step T2 location. In both the double-step task and the memory-guided saccade task, the monkey made a saccade from the T1 location to the remembered T2 location. Only in the double step task must the representation of the remembered location must be updated. Therefore if behavior is correlated with remapping, or updating of the representation, a relationship should only be observed for the double-step task.

We looked for a correlation between distance error and memory-guided saccade activity for each neuron recorded in the split brain monkeys. We found no relationship between firing rate and saccade accuracy. This lack of correlation was found both when the within and across trials were combined (mean r = 0.04, P = 0.19, sign test) and when they were separated (within: mean r = −0.04, P = 0.06; across: mean r = 0.05, P = 0.47, sign test). The results from this control task tell us that the relationship we did observe between remapping activity and performance on the across condition of the double-step task cannot be due to saccade activity alone. If it was due to the eye movement alone, we would have seen a correlation between performance and firing rate in the memory-guided saccade task. The finding that there is no correlation between activity and distance error during the memory-guided saccade task supports the idea that when the primary pathway between the hemispheres is disrupted, the SC plays a role in behavior on the double-step task.

In the superficial layers of the SC, we found no difference in the magnitude of response for within and across conditions of the double-step task. We thus expected to find no relationship between neural activity and behavior on a trial-by-trial basis. Our expectations were confirmed when the trials for within and across conditions were combined. We found that the distribution of r values was not significantly shifted from zero for the split brain monkey (Fig. 11A, mean r = −0.11, P = 0.34, sign test). When we separated the analysis for within and across conditions, we found that there was a significant shift for the within conditions but not for across (Fig. 11C, within: mean r = −0.17, P = 0.04; E, across: mean r = −0.13, P = 0.18, sign test). We also found a significant relationship between neural activity and behavior for the within only conditions for the MGS analysis (mean r = 0.12, P = 0.04). This relationship was in the opposite direction as the relationship between neural activity and behavior for the double-step task. We found no significant shift in the intact monkey for both the combined and separated analysis (Fig. 11, B, D, and F). In sum, when the forebrain commissures are transected, in the superficial layers of the SC, firing rate is not correlated with accurate performance.

**Double-step neuronal activity is related to saccade latency.** We used a second behavioral measure, latency of the second saccade, to examine the relationship between remapping activity and performance. We calculated the relationship in two ways. First, we combined trials from both the within and across conditions. In the second analysis, we separated trials by condition. In the intermediate layers of the SC of the split brain
monkey, we found a significant relationship only when the across trials were analyzed separately (Fig. 12E, mean $r = 0.17, P < 0.01$; $E$, across: mean $r = 0.21, P < 0.001$, sign test). We found no relationship between remapping activity in the superficial layers of the SC and saccade latency for the intact monkey (Fig. 13, $B$, $D$, and $F$). We also found no relationship between activity recorded from neurons in the superficial layers of the SC during the MGS task and saccade latency. This was true for both the split brain and intact monkeys. Therefore the relationship observed between remapping activity and saccade latency in the split brain monkeys cannot be due saccade related activity alone.

The results from the trial-by-trial analyses are summarized in Table 3. For area LIP, we found a relationship between remapping activity and performance on the double-step task only when within and across trials were combined. This was the case for two measures of performance: accuracy and latency of the second saccade. There was no relationship when the conditions were analyzed separately. For the intermediate layers of the SC, we found a relationship between both measures of performance and remapping activity only when the across trials were analyzed separately. Finally, for the super-

**FIG. 11.** Trial-by-trial analysis for superficial layers: relationship between remapping activity and 2nd saccade (S2) distance error. Panels show the distribution of $r$ values for the trial-by-trial correlation between remapping activity from the superficial layers of the SC and S2 error. Only for split brain monkeys during within-hemifield trials (C) is the distribution of $r$ values significantly shifted from 0. Conventions same as in Fig. 10.

In the superficial layers of the SC we found that there was a significant relationship between remapping activity and saccade latency when the trials were combined for within and across and when the trials were separated. When the trials were combined, the relationship was shifted toward the positive; with higher firing rate, there were longer saccade latencies (Fig. 13A, mean $r = 0.18, P < 0.001$, sign test). When the trials were separated, there were significant positive relationships for both within and across conditions (Fig. 13C, within:
official layers of the SC, we found a relationship between saccade latency and remapping activity when the within and across trials were combined as well as when they were separated. These results suggest that in the absence of the forebrain commissures, activity in the SC contributes to the behavior of the monkey.

**DISCUSSION**

Our main goal is to understand the circuitry that underlies remapping. In previous studies, we investigated the mechanism for updating visual information from one visual field to the other (Berman et al. 2005, 2007; Heiser et al. 2005). We transected the forebrain commissures and expected to find that remapping would be abolished when memory traces had to be remapped across the vertical meridian. Instead we found that neurons in area LIP are capable of remapping memory traces across hemifields even in the absence of the forebrain commissures. Moreover, we found that the monkeys could use remapped visual information to guide behavior. In the current study, we asked whether there was remapping in a subcortical structure, the SC, in the split brain monkeys.

We have five main findings. First, in split brain monkeys, neurons in the superficial and intermediate layers of the SC are capable of remapping visual information both when it remains within and when it is transferred across hemifields. Second, the strength of remapping differed in the intermediate and superficial layers. In the intermediate layers of the split brain monkeys, remapping across hemifields was reduced compared with remapping within a hemifield. In contrast, in the superficial layers of the split brain monkey, magnitude of remapping was similar for within and across hemifields. Third, in the intermediate layers of the SC, remapping activity was delayed for across compared with within hemifield. The timing of remapping in the superficial layers was not different for across and within hemifield. Fourth, the accuracy of performance in the double-step task was correlated with the activity of neurons in the intermediate layers of the SC in the across-hemifield trials. In the superficial layers, accuracy was correlated with activity for within-hemifield trials during the double-step task, probably due to saccade related activity. Fifth, the latency of the second saccade was correlated with activity of neurons in the intermediate layers of the SC in the across-hemifield trials. In the superficial layers, activity was correlated with the latency of the second saccade for both within and across trials. We conclude that there are differences in remapping between the layers of the SC.

**TABLE 3. Trial-by-trial correlation between of behavior and neuronal activity**

<table>
<thead>
<tr>
<th></th>
<th>Split-Brain</th>
<th>Intact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance error</td>
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</tr>
<tr>
<td>compared to</td>
<td>Negative correlation: across trials only</td>
<td>None</td>
</tr>
<tr>
<td>remapping activity</td>
<td>Negative correlation: combined trials only</td>
<td>None</td>
</tr>
<tr>
<td>Superficial SC</td>
<td>Positive correlation: within trials only</td>
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</tr>
<tr>
<td>Intermediate SC</td>
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<td>None</td>
</tr>
<tr>
<td>LIP</td>
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<tr>
<td>Distance error</td>
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<td>compared to</td>
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<td>Second saccade</td>
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<td>Intermediate SC</td>
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</tr>
<tr>
<td>LIP</td>
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</tbody>
</table>

**FIG. 13.** Trial-by-trial analysis for superficial layers: relationship between remapping activity and 2nd saccade (S2) latency. Panels show the distribution of r values for the trial-by-trial correlation between remapping activity from the superficial layers of the SC and the latency of the S2. The distribution of r values are significantly shifted from 0 for the split brain animals only for all trials (A, C, and E). Conventions same as in Fig. 10.
ping activity in the intermediate layers reflects activity in cortex. Remapping activity in the superficial layers is not affected by removal of the forebrain commissures. Activity in the SC that originates independent of the cortex may be a source of the preserved remapping in area LIP in the split brain monkeys.

Neural circuits for remapping observed in the intermediate layers of the SC: corticotectal and tectocortical pathways

In split brain monkeys, remapping activity in the intermediate layers of the SC resembles remapping activity in area LIP. For both brain regions, across-hemifield remapping is attenuated compared with within-hemifield remapping. Across-hemifield remapping is also delayed compared with within-hemifield remapping. The forebrain commissures connect the cortical hemispheres; they do not connect the superior colliculi. In the split brain animals, nothing has been done to the SC connections. The changes in remapping activity that we observed in the SC of the split brain monkeys must reflect cortical inputs, possibly from area LIP. LIP has direct projections to the intermediate layers of the SC, which would allow it to transmit remapped visual information (Ferraina et al. 2002; Leichnetz 2001; Lynch and Tian 2005; Pare and Wurtz 1997, 2001).

While our data only demonstrate a transfer of activity from LIP to SC, other studies suggest that the reverse relationship also exists. Activity in the SC could influence activity in cortex through a multisynaptic pathway. The SC does not project directly to cortex; the thalamus relays information from the SC to cortex. A small minority of neurons in intermediate layers of the SC send a disynaptic connection to area LIP through the pulvinar (Benevento and Rezak 1976; Clower et al. 2001; Leichnetz 2001). The functional role of this projection remains unknown. One possibility is that neurons that project from the intermediate layers of the SC to area LIP are the source of the preserved across-hemifield remapping. Some intermediate layer SC neurons had equivalent remapping for within and across hemifields. There are two explanations for the equivalent remapping. First, some neurons in area LIP also have equivalent remapping for within and across hemifields; therefore activity in the intermediate layers of the SC could reflect activity in area LIP. Second, the SC neurons with similar remapping between the two conditions might remap independent of cortex. Remapping could occur entirely within the SC or be passed to the SC from another subcortical source. These neurons that remap independent of cortex may be the source of the across-hemifield remapping in area LIP of the split brain monkeys.

While remapping activity may be passed from the SC to area LIP, the disynaptic projections, particularly from the intermediate layers of the SC to area LIP, are limited (Clower et al. 2001). Less direct pathways from the intermediate layers of the SC to area LIP also exist. For example, the medial dorsal (MD) nucleus projects to area FEF, which in turn projects to area LIP (Andersen et al. 1990; Bullier et al. 1996; Chafee and Goldman-Rakic 1998, 2000; Petrides and Pandya 1984; Schall et al. 1995; Sommer and Wurtz 2000, 2004; Stanton et al. 1995). While multiple signals are passed from the SC through MD to the FEF, activity directly before the saccade is particularly important (Sommer and Wurtz 2004). This presaccadic activity is thought to be a corollary discharge signal. Corollary discharge, a copy of the motor command to move the eyes, is necessary for updating of visual representations. It is possible that remapping activity is transferred from the SC through MD to the FEF.

Neural circuits for remapping observed in the superficial layers of the SC: corticotectal and tectocortical pathways

The results from the superficial layers contrast with those from the intermediate layers and the area LIP results. Activity in superficial layers of the SC is not influenced by activity from area LIP. It is more likely that the superficial layers of the SC pass information to area LIP. The majority of the disynaptic connections from the SC to area LIP originate in the superficial layers, not the intermediate layers (Benevento and Rezak 1976; Clower et al. 2001; Leichnetz 2001). This pathway may be the source of the preserved across-hemifield remapping observed in split brain animals.

Cortical areas other than area LIP may influence activity in the superficial layers. The superficial layers receive projections from striate and prefrontal visual cortex, as well as the FEF (Distler and Hoffmann 2001; Finlay et al. 1976; Fries 1984; Huerta and Harting 1984; May 2005; Schiller et al. 1974; Wurtz and Albano 1980). Potentially other cortical areas influence activity in the SC, and these cortical areas may exhibit no difference between within- and across-hemifield remapping in the split brain animals.

Neural circuits for remapping observed in the SC: tectocortical pathways

If neurons in intermediate and superficial layers remap independent of cortex, then they must either pass information between the two colliculi or there must be another subcortical source of remapping. Each colliculus represents the contralateral visual field in a retinotopically organized map (Cynader and Berman 1972). For a neuron to show remapping activity during the cross condition, it must receive information from the ipsilateral visual field. It could be that information passes from one colliculus to the other through the intertectal commissure (Behan and Kime 1996a,b; Edwards 1977; Lee and Hall 2006; Lee et al. 2001; Moschovakis et al. 1988; Munoz and Istvan 1998; Olivier et al. 1998, 2000; Tardif and Clarke 2002; Yamasaki et al. 1984). Anatomical and physiological studies have confirmed the presence of inhibitory and excitatory connections (Behan and Kime 1996a,b; Lee and Hall 2006; Lee et al. 2001; Moschovakis et al. 1988; Olivier et al. 1998, 2000). Tectocortical neurons are present throughout the mediolateral and rostrocaudal extent of the SC (Olivier et al. 1998). Most tectocortical cells are located in the intermediate layers; a small proportion are located in the superficial layers. The presence of these connections leaves open the possibility that the intertectal commissure is a pathway for remapping activity. Through this pathway, visual information could be transferred across hemifields. However, these intertectal connections would not suffice for remapping to occur in the superficial layers. Remapping also requires information about the saccade, in other words, a corollary discharge signal. The superficial layers are purely visual; the neurons do not encode saccades. The intermediate layers, however, do have saccade...
related activity. Anatomical and physiological studies have demonstrated that activity can pass from the intermediate to the superficial layers (Isa 2002; Lee et al. 2007; Richmond and Wurtz 1980; Tardif et al. 2005; Wurtz and Mohler 1976; Yamasaki et al. 1984). One proposed function of these connections is a pathway for suppression of activity around the time of a saccade (Lee et al. 2007; Richmond and Wurtz 1980). The activity of many superficial cells is suppressed during saccades (Goldberg and Wurtz 1972; Robinson and Wurtz 1976). A second function could be enhancement of the visual response (Wurtz and Mohler 1976). The activity of many superficial cells is enhanced if a stimulus is a target for an eye movement. Both suppression and enhancement depend on information about the eye movement (Richmond and Wurtz 1980; Wurtz and Mohler 1976). Projections from the intermediate layers to the superficial layers may provide a corollary discharge signal necessary for remapping.

Other pathways for subcortical remapping

Although SC seems the most likely subcortical structure to contribute to remapping, other subcortical regions may be involved. The intertectal commissure contains fibers that connect subcortical structures other than the colliculi (Antonetto and Webster 1975; Edwards 1975, 1977; Jayaraman et al. 1977; Wallace et al. 1989, 1990). For example, many studies have demonstrated that the projections from the substantia nigra pars reticulata (SNr) to the SC are important for visual orienting and saccadic eye movements (Basso and Liu 2007; Basso et al. 2005; Hikosaka and Wurtz 1983a,b; Liu and Basso 2008; Wallace et al. 1989, 1990). While it is thought that the main role of the SNr is to provide an inhibitory signal to the SC, the potential role of the SNr in remapping has not been explored.

A second potential subcortical pathway involves the cerebellum. Visual information is transferred from cortical visual areas and the SC to the pontine nuclei which project to the cerebellum (Baker et al. 1976; Glickstein et al. 1980; Mower et al. 1980). The cerebellum then projects back to the deeper layers of the superior colliculus (Huerta and Harting 1984). This could allow remapping signals to be relayed back to the SC and cortical areas. Remapping activity in these pathways has yet to be explored.

Remapping activity and the behavior of the monkey

Many brain areas have neurons capable of remapping (Berman and Colby 2009). How these areas interact to contribute to behavior remains unknown. We began to address this question by recording from neurons in area LIP and the SC while split brain and intact monkeys performed the double-step task. We found that for the intermediate layers, there was a negative correlation between remapping activity and performance only for the across conditions. There are two possible explanations for a significant response only for the across trials. First, the monkeys’ performance on the across conditions was less accurate. From trial to trial, there was more variability in saccade endpoints. Because there was greater variability, a relationship could be more easily detected. Second, it is possible that when the primary pathway that connects the two cortical hemispheres is removed, activity in a subcortical structure becomes more important for the behavior of the monkey. Many models have been proposed that suggest that decisions are made based on accumulation of evidence to a threshold (Glimcher 2001; Gold and Shadlen 2002; Leon and Shadlen 1998; Romo and Salinas 2001; Schall 2001). Multiple populations of neurons with different preferred responses pool their signal. Once a group of neurons reach a threshold, a response is made. It may be that accurate performance in the double-step task depends on precise pooling of remapping signals from many brain areas. This pooling process is undoubtedly affected when the forebrain commissures are transected. When firing rate is low, as in the case in the across condition, the proper threshold is not reached and an inaccurate saccade is made. When firing rate is high, a correct saccade is made. In other words, there is a negative relationship; higher firing is related to decreased error.

In the superficial layers of the SC, we found a significant relationship between remapping activity and latency of the second saccade. When the neurons fired more, the saccade latency was shorter. This relationship held when the within and across conditions were combined and when the conditions were separated. This increase of activity with shorter saccades suggests that activity builds to a threshold before a saccade is initiated. When activity reaches the threshold sooner, the saccade occurs sooner. What is remarkable about the relationship between activity of superficial layers and saccade latency is that neurons in the superficial layers of the SC are thought to be purely visual (Wurtz and Mohler 1976). This correlation between neuronal activity and saccade latency in superficial layers of the SC of the split brain monkeys is further evidence that when the forebrain commissures are transected, remapping activity in the SC becomes more important for behavior.

Spatial updating and humans

Several lines of evidence suggest that the circuits that underlie remapping in monkeys and humans are similar. In humans, remapping activity has been described in parietal as well as in striate and extrastriate cortex (Merriam et al. 2003, 2007). Several studies suggest that information about spatial locations can be transferred between hemispheres in the absence of the forebrain commissures (Corballis 1995; Hines et al. 2002; Holtzman 1984; Holtzman et al. 1981; Mooshagian et al. 2009; Ptito et al. 2009; Reuter-Lorenz and Fendrich 1990). The SC is thought to be involved in for the interhemispheric transfer of visual information in split brain patients (Savazzi and Marzi 2004; Savazzi et al. 2007). It is possible that in split brain humans, as in split brain monkeys, remapping activity is present in the SC and is transferred to cortex.

Conclusions

The results described here lead to three conclusions about the circuitry of remapping in intact animals. First, as previously shown, the primary pathway for across-hemifield remapping in the intact monkey is the forebrain commissures. Second, remapping activity is transferred from cortex to the intermediate layers of the SC. This pathway must exist in the intact animal, otherwise we would see no difference in activity between split brain and intact animals in the SC. Third, there are multiple circuits that underlie remapping. When one path-
way is damaged, another pathway can become more important. In the absence of the forebrain commissures, activity in the intermediate and superficial layers of the SC is related to spatial behavior. This is particularly interesting for the superficial layers of the SC, which was thought to be purely visual (Wurtz and Mohler 1976). Yet remapping activity is related to the latency of the second saccade in the split brain animals. When the primary pathway for remapping is damaged, activity in this “visual” area is related to the monkey’s behavior. These results demonstrate that there is considerable plasticity in the circuitry that produces visual stability.

ACKNOWLEDGMENTS

We thank K. McCracken and Dr. Kevin Hitchens for technical assistance and J. Patrick Mayo and other colleagues at the Center for the Neural Basis of Cognition for constructive comments.

GRANTS

This work was supported by National Institutes of Health Grants EY-12032 and MH-45156, technical support was provided by Core Grant EY-08908, and collection of MR images was supported by P41RR-03631. Support was also provided by National Aeronautics and Space Administration Fellowships to C.A. Dunn.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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J Neurophysiol • VOL 104 • SEPTEMBER 2010 • www.jn.org

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